Hydrogeology

of the

Upper Selwyn Catchment

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Selwyn River at Glentunnel

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Abstract

Farming practices within the upper Selwyn plains have significantly expanded, and are becoming more dependent on groundwater as a reliable source of irrigation. This expansion has resulted in the rapid development of the groundwater resource and water levels in many wells have reached record low levels.

Groundwater resources can be found within at least three aquifers within the glacial gravel deposits of the upper Selwyn plains. Aquifer 1 occurs between approximately 0 – 30m, aquifer 2 between 40-85m and aquifer 3 greater than 100m below the surface. Aquifers 1 and 2 occur within close proximity to the Selwyn River and its tributaries. Aquifer 1 is unconfined, aquifer 2 semi-confined and aquifer 3 semi-confined to confined. Significant leakage of groundwater occurs between the different aquifers.

Recharge sources to the aquifers include rainfall infiltration, runoff and infiltration of rainfall falling on the foothills and seepage of river water. Water levels and groundwater chemistry suggest that the Selwyn River provides the dominant source of recharge to aquifers 1 and 2 in areas immediately surrounding the river and to the south of the current course of the river between Greendale and Dunsandel.

Acknowledgments

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Chapter One

Introduction

1.1 Project Background

Farming practices within the upper Selwyn plains, like many other areas within the Canterbury region, are expanding and becoming more dependent on groundwater as a reliable source of irrigation. This expansion, together with a trend to more intensive farming practices, in particular dairying, has resulted in the rapid development of the groundwater resource and water levels in many wells have reached record low levels. In order to successfully manage the water resources a better understanding of the surface and groundwater systems are required.

1.2 Objectives

The overall aim of this investigation is to obtain a comprehensive understanding of the surface and groundwater resources within the upper plains portion of the Selwyn catchment. Primary objectives include:

- Delineating the different aquifers and their properties
- Establishing the relationship between surface water bodies and the groundwater resource
- Establishing trends in groundwater chemistry both spatially and with depth and comparing samples to the New Zealand water quality standards
- Distinguishing groundwater recharge sources through the use of water chemistry and/or oxygen-18
- Determining the age of the groundwater resources and to discuss any implications for groundwater management
- Establishment of recommendations for future monitoring programmes to ensure the groundwater resource is effectively managed

1.3 Study Area

The study area is an approximately 280 km^2 area within the upper plains portion of the Selwyn catchment between the Waimakariri and Rakaia rivers (figure 1.1). The Selwyn catchment is located within the Canterbury region on the east coast of the South Island, New Zealand. Field

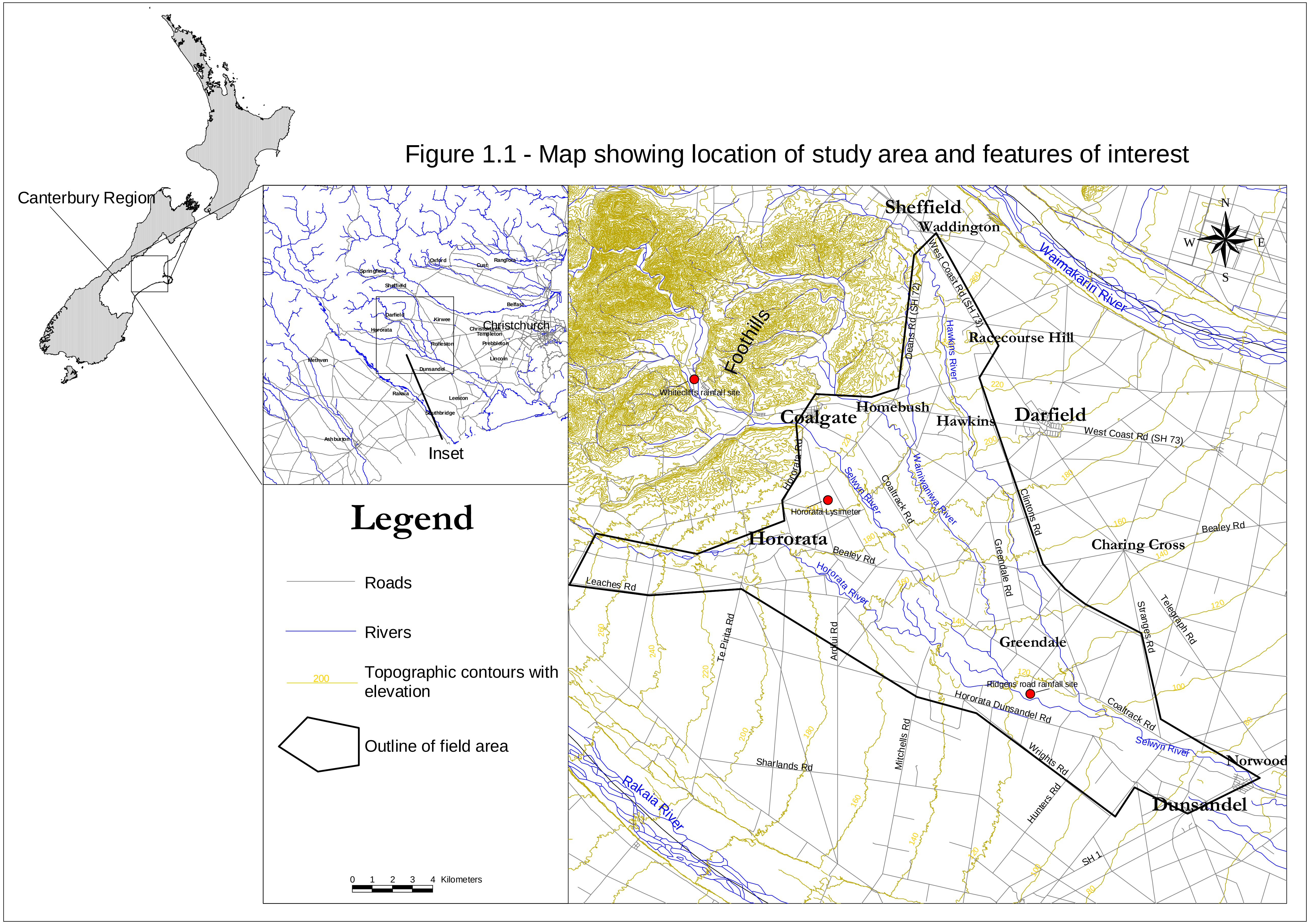


Figure 1.1 - Map showing location of study area and features of interest

boundaries were loosely established to include areas in which groundwater was most likely to be influenced from local rivers, and in some instances investigations extended beyond those boundaries in order to obtain a better understanding of the groundwater system.

The field area occurs within the Rakaia-Selwyn and Selwyn-Waimakariri groundwater allocation zones of Aitchison-Earl et al (2004) (figure 1.2). These groundwater allocation zones were developed to protect aquifers from over-abstraction and maintain the reliability of groundwater to existing users. The allocation limit for each zone was calculated from the best available information on recharge sources within each zone. Based on this information the Rakaia-Selwyn zone was estimated as being over 100% allocated, and the Selwyn-Waimakariri zone between 80% and 100% allocated.

1.4 Physical Setting

1.4.1 General Setting

The Canterbury plains are composed essentially of Quaternary age gravels deposited from rivers during glacial periods. A number of aquifers occur within these gravels where the gravels are sufficiently permeable to allow water movement. The foothills are composed dominantly of Mesozoic greywacke of the Torlesse Supergroup but Tertiary aged sediments and volcanics also outcrop within the foothills to the west of the field area.

The major river in the field area is the Selwyn River. The Selwyn River is ephemeral and typically runs dry soon after its emergence from the foothills, but may flow along its full length for a few months of the year. The Selwyn River has three tributaries, the Hororata, Hawkins and Waianiwaniwa (formerly Waireka) rivers, which all typically run dry in their upper plains reaches.

1.4.2 Climate

Most rainfall within the Selwyn catchment is associated with cold southerly air masses (Sturman, 1986). However, some rainfall occasionally reaches the plains from northwest winds which are responsible for bringing most precipitation to the Southern Alps. Figure 1.3 shows that mean annual rainfall on the plains increases from about 700mm in the mid plains region to 1000mm towards the foothills.

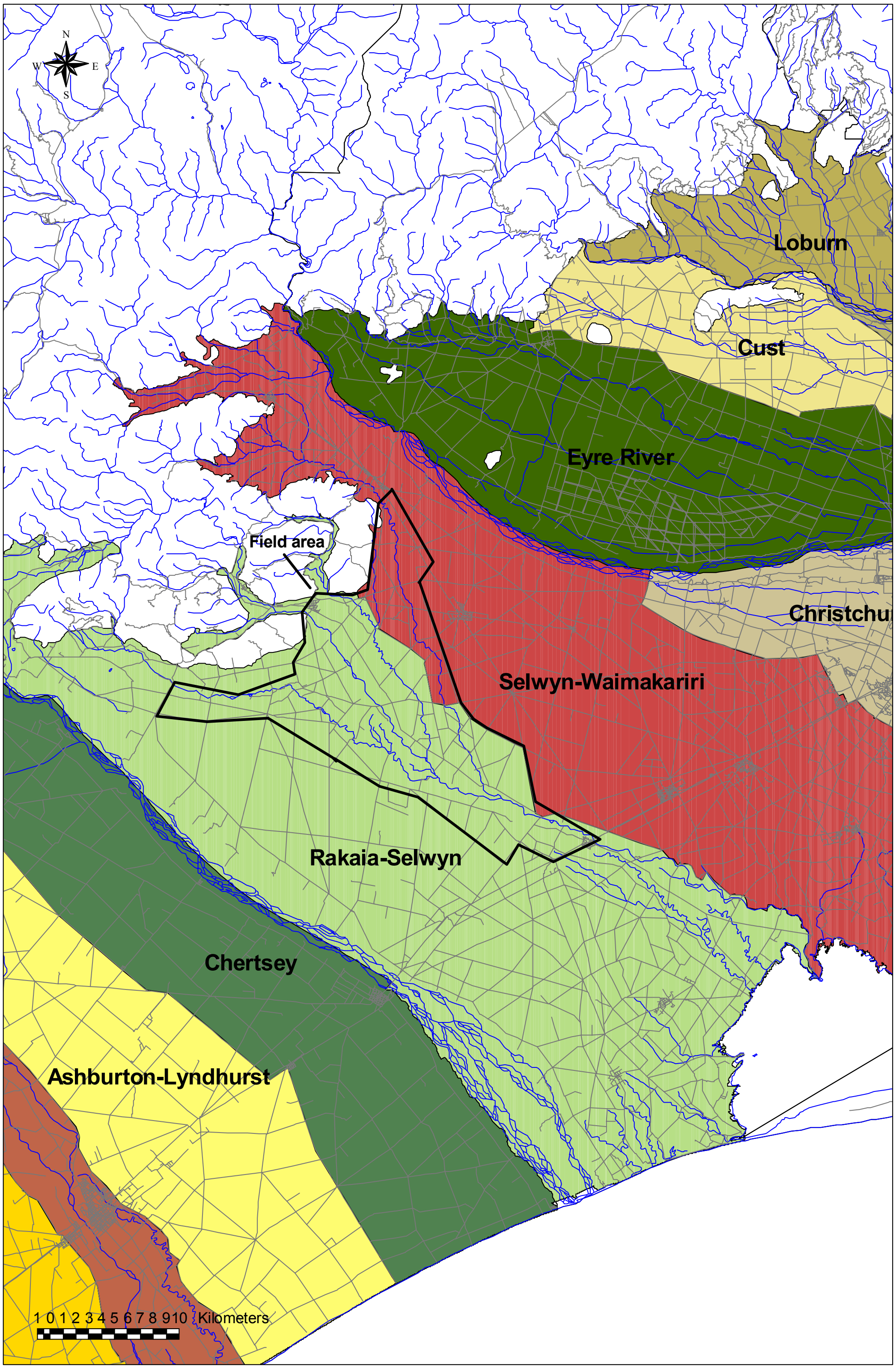


Figure 1.2 Groundwater Allocation zones of Aitchison-Earl et al (2004) and location of field study boundaries (different zones are shown as different colours).

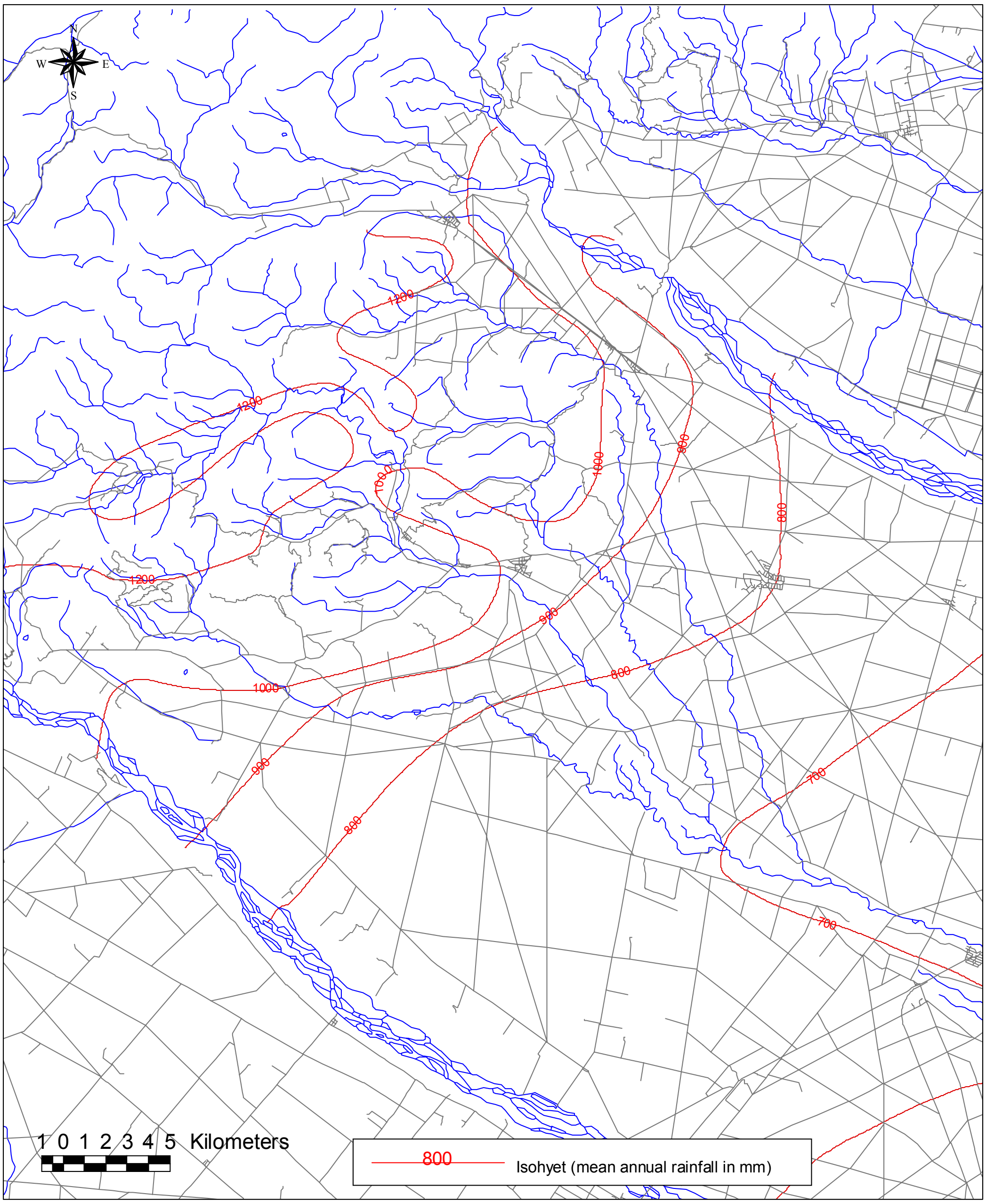


Figure 1.3 Mean annual rainfall on Selwyn plains and foothills. Source: Environment Canterbury.

Mean monthly rainfall data for Environment Canterbury's Whitecliffs and Ridgens road rainfall sites, located at the edge of the foothills and in the middle of the field area respectively (figure 1.1), are shown in figure 1.4. The data for Whitecliffs shows that rainfall is more or less uniformly spread on the foothills throughout the year, whilst the Ridgens road data shows that rainfall on the plains is highest during the winter/spring months of June, July, August and September.

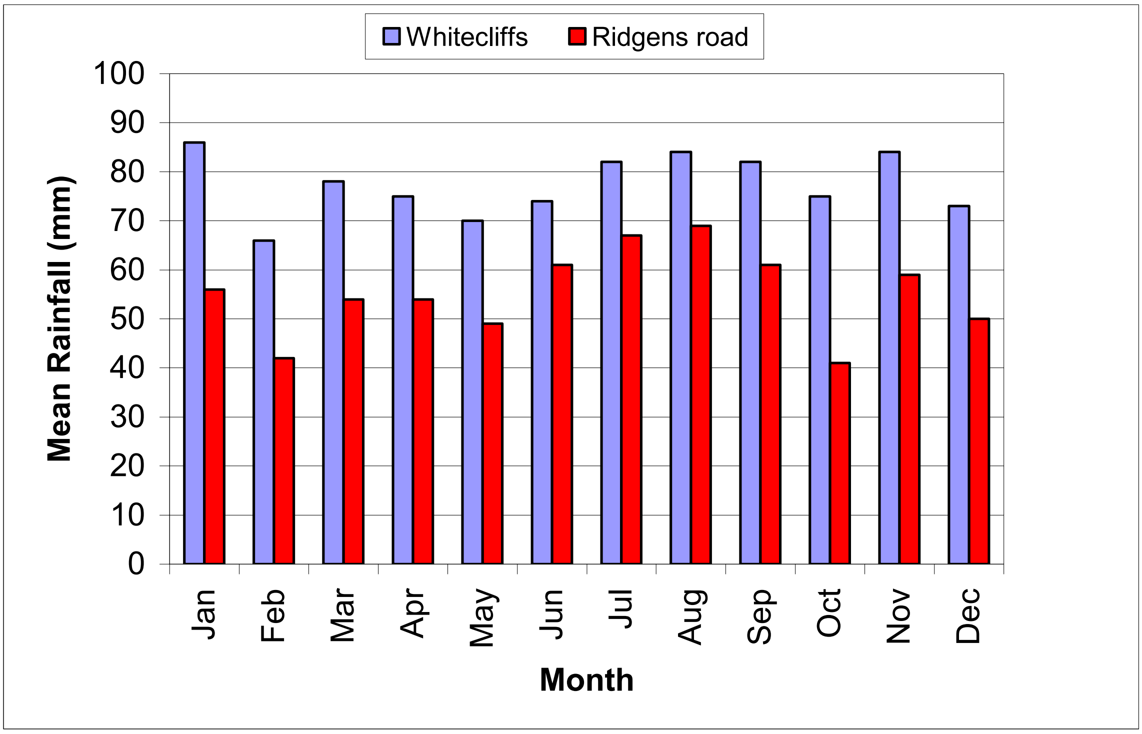


Figure 1.4 Comparison of mean monthly rainfall (mm) for Whitecliffs (1988-2004) and Ridgens road (1990-2004).

Evaporatranspiration calculated for the Hororata Lysimeter, which is located within the upper plains of the field area (figure 1.1), is highest during the summer months of December and January (figure 1.5). High evapotranspiration rates limit the transport of rainfall or irrigation water through the soil.

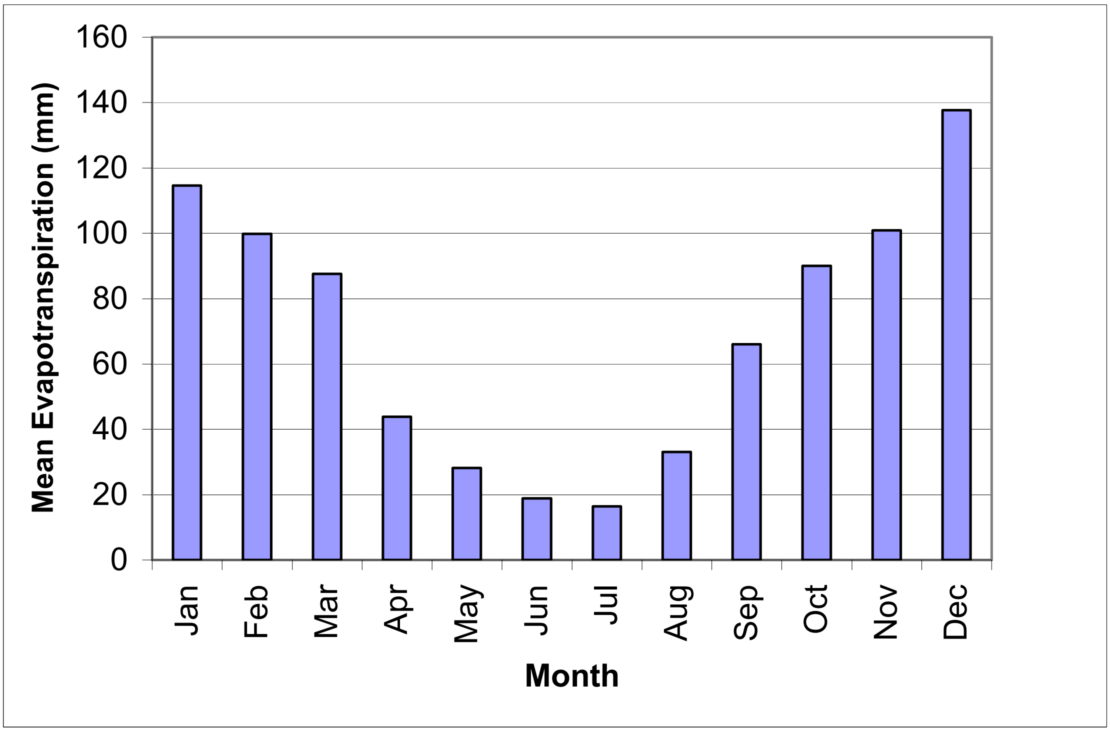


Figure 1.5 Mean evapotranspiration (mm) for Hororata Lysimeter (1999-2004).

The irrigation season typically runs from October or November until March or April, but is very dependant on rainfall and soil moisture levels. Summers on the Canterbury plains are often hot and dry with near-drought conditions a regular occurrence.

1.4.3 Soils

The soils within the upper and mid Selwyn plains have developed over permeable gravel fans, terraces and floodplains that have been blanketed with loess of varying thickness (Taylor, 1996). The average profile available water (PAW avg) for soils within the area are shown in figure 1.6 where PAW is defined as the amount of water (in mm) that the soil can hold that plants can reasonably be expected to use. Figure 1.6 shows that the average PAW for soils overlying gravel deposits within the upper plains of the Waimakariri and Rakaia rivers are typically between 80-95mm and 60-80 mm respectively. These soils are dominantly Yellow Grey Earth Lismore or Chertsey soils. In contrast, the average PAW for soils overlying Selwyn fan gravels (i.e. soils between the Hororata and Hawkins rivers) are extremely variable and ranges from 25mm to over 95mm. These latter soils are dominantly composed of Recent Waimakariri, Shallow Waimakariri, Eyre-Paparua or Templeton soils. A detailed description of soils within the region can be found in Soil Bureau (1968).

1.5 Land Use and Water Development

Land use throughout the upper Selwyn plains is variable. Sheep, beef, dairying and crop are the major farming activities with deer, piggeries and horticulture less prominent (Taylor, 1996). Dairying has increased significantly from the 1990s because of higher financial returns but requires large amounts of water for irrigation and production. Agricultural production on the plains is generally higher and more diverse where there is a reliable source of irrigation. Typical flat-lying farmland within the field area is shown in figure 1.7.

The earliest recorded wells within the field area were likely sunk during the early and middle 1900s as settlers occupied the plains and drinking and stock water supplies were needed. They were typically shallow (less than 20m deep) 1m diameter brick-lined wells or 50mm diameter windmill driven wells, located within close proximity to the Selwyn River because of the higher water table and lower depth required to obtain water next to the river. Some older brick-lined and windmill driven wells within the field are shown in figure 1.8. The shallow nature of these wells, together with their close proximity to the ephemeral Selwyn River and low pumping

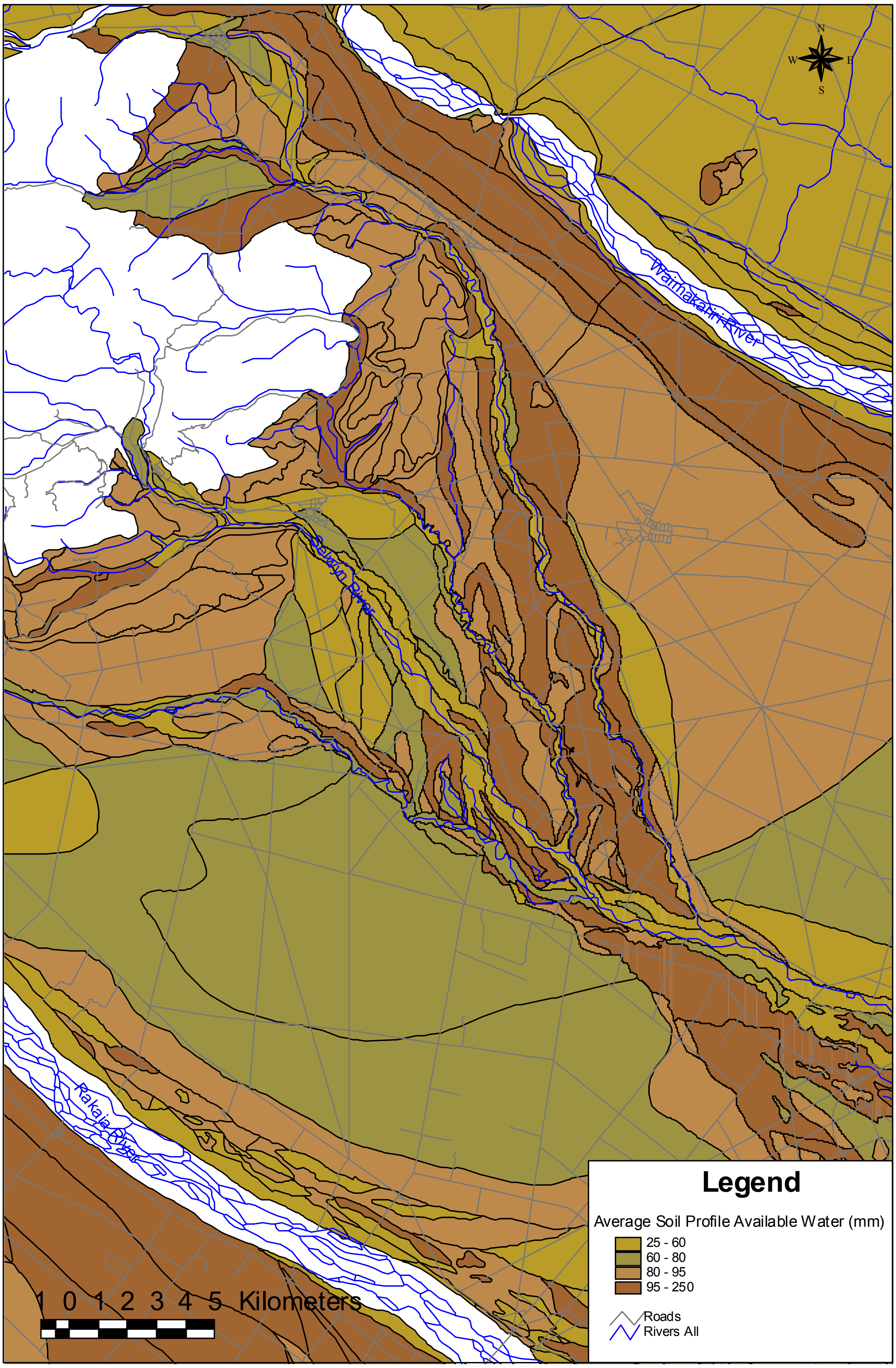


Figure 1.6 Map of average profile available water (PAW avg) for soils within the Selwyn plains.

rates, meant that these wells were unreliable and unsuitable for irrigation. Most of these older wells are now disused or have been filled in. Recent wells are typically composed of steel casing, can be drilled to depths well in excess of 200m and capable of pumping groundwater at rates greater than 100 litres per second. A typical modern well is shown in figure 1.8.

Figure 1.7. Typical flat lying irrigated farmland within the upper Selwyn plains with foothills in the background.

The number of wells drilled with time within the field area is shown in figure 1.9[1]. Figure 1.9 shows that the number of wells has steadily increased from the 1950s to the present day, with a particularly large number of wells drilled during the periods 1990-2000 and 2000 to the present. The recent increase in drilled wells can be largely attributed to the expansion from dryland farming to more intensive farming practices requiring a reliable source of groundwater for irrigation (Brown, 2000). This expansion and has resulted in increasing pressure on the groundwater resource.

[1] Only 270 of the 600 existing wells within the field area had recorded drill dates.

Figure 1.8 Photographs of disused 1m diameter old brick-lined well (top), disused 50mm diameter windmill well (middle) and typical modern bore (below).

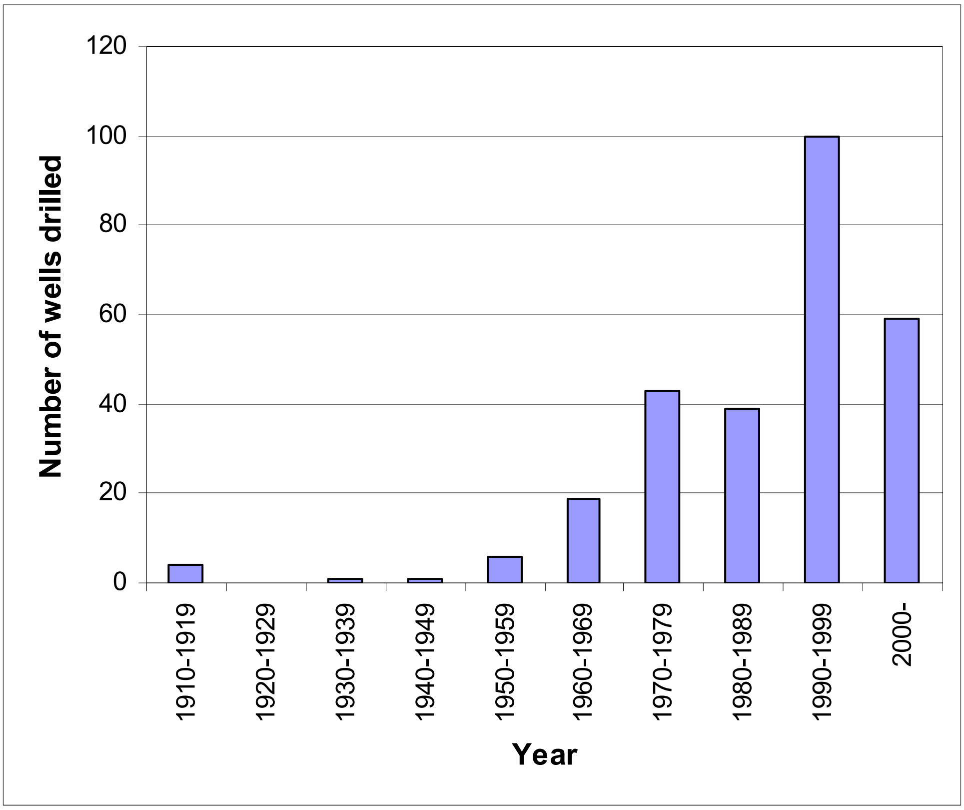


Figure 1.9. Number of wells drilled with time within the field area.

The effect of the recent increase in drilled wells on the groundwater resource is illustrated in figure 1.10 which shows total groundwater abstractions in cubic metres per day per square kilometre for 1995 and May 2005. Figure 1.10 shows that groundwater abstractions have expanded in most areas within the field area but particularly to the south of the Selwyn and Hororata rivers.

As of April 2005 there were roughly 600 existing wells within the field area. Approximately 250 of these wells are used principally for irrigation and 300 for domestic or stock water purposes. Shallow wells (less than 30 metres in depth) make up about 57% of all wells within the field area, 32% are between 30 and 100 metres, and 11% are deeper than 100 metres. A map of well distribution and depth (figure 1.11) shows a definite trend to deeper wells with distance from the major rivers. In addition to the existing wells there were approximately 50 proposed wells within the field area as of May 2005 (figure 1.12). The majority of these wells are located within the Greendale and Hororata areas and have proposed depths greater than 85m. In general, there has been a recent trend to drilling deeper wells in order to obtain a more reliable source of irrigation and to avoid any adverse effects to river or stream flows.

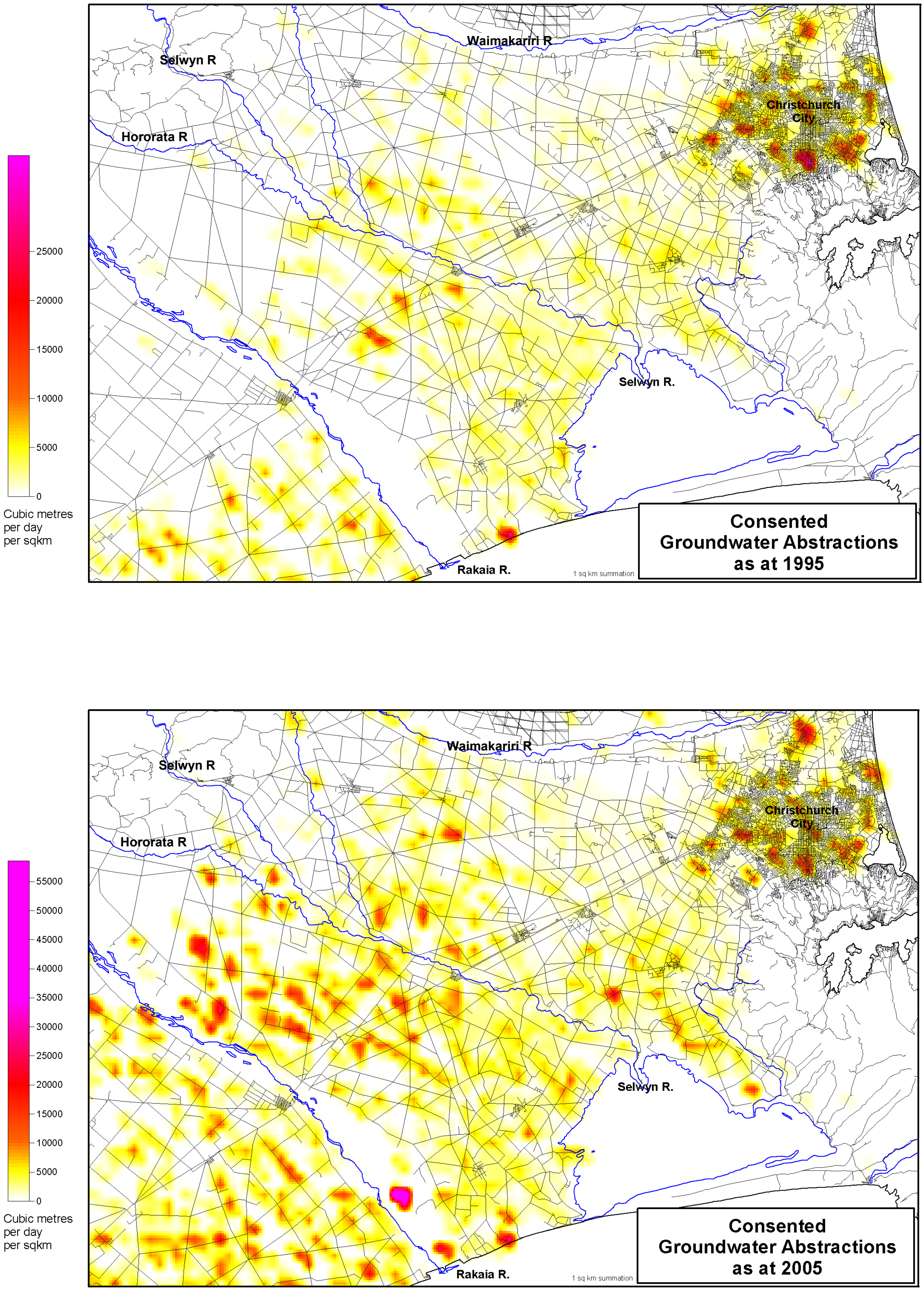


Figure 1.10. Consented groundwater allocation (m^3/day per km^2) between the Waimakariri and Rakaia rivers in 1995 (top) and May 2005 (below).

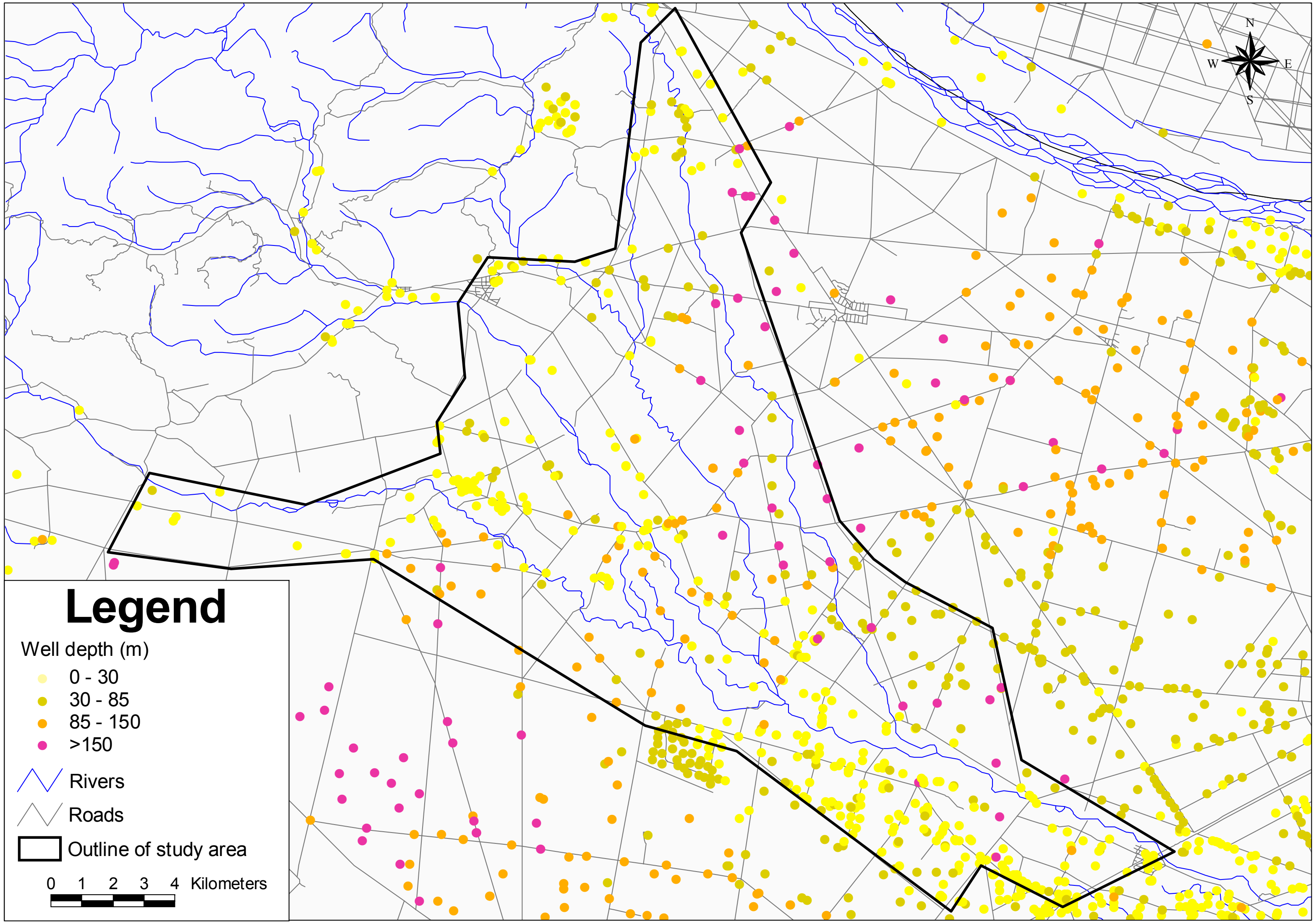


Figure 1.11 Well distribution and depth.

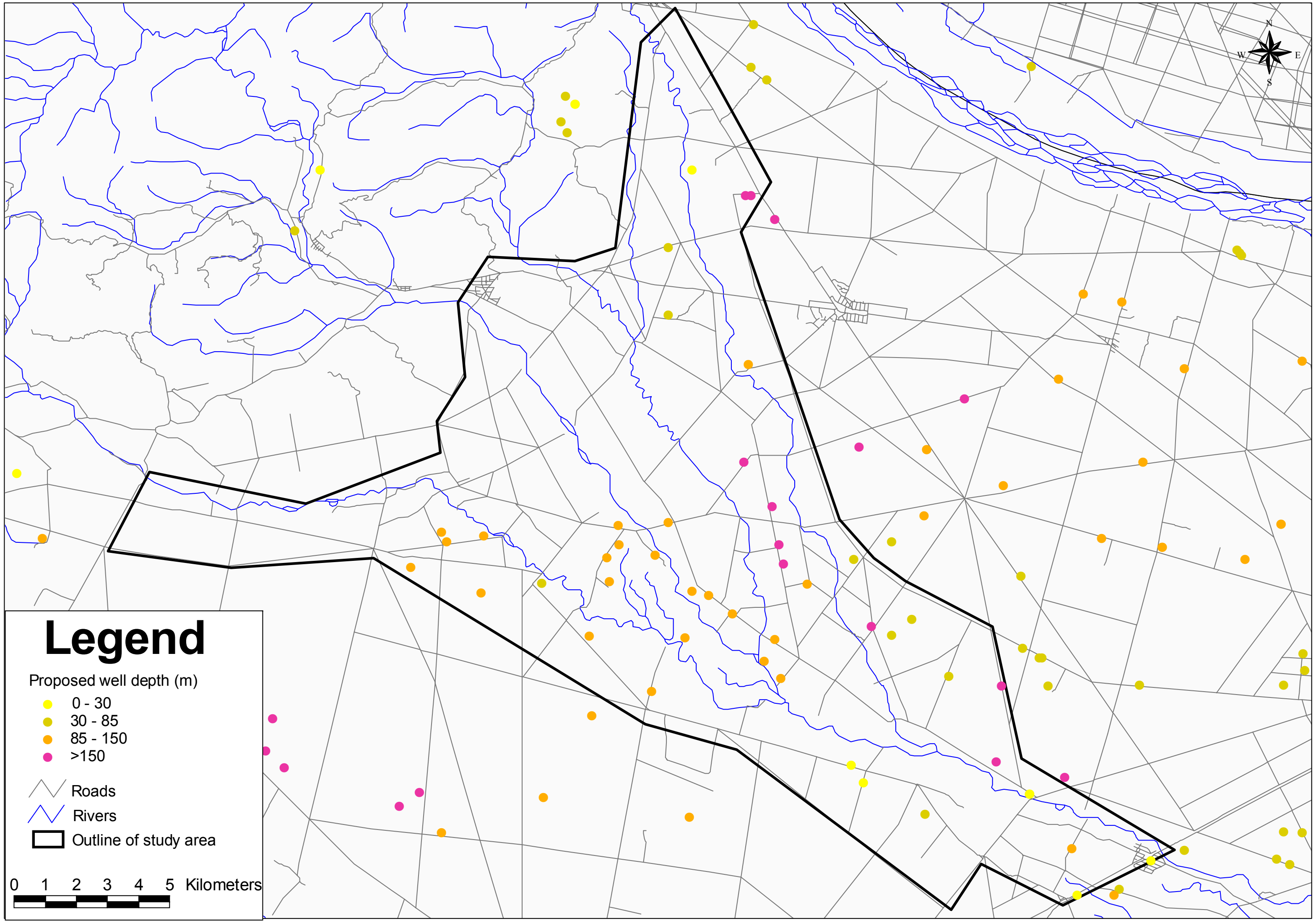


Figure 1.12 Proposed wells.

1.6 Previous Work

The earliest hydrogeological research within the field area was performed in the early to middle twentieth century and was dominantly focused on finding suitable groundwater-sourced public water supplies for the major townships. Gair and Collins (1950) investigated the possibility of obtaining a groundwater sourced water supply for Darfield township. Potential problems included the presence of a low water table (greater than 70m depth to water) and uncertainty of whether water could be obtained at a sufficient quantity to supply the town. Oborn (1952) examined the possibility of supplementing flow in the Hawkins water race (now non-existent) from groundwater within the Racecourse Hill and Sheffield areas. Brown (1966) further investigated the possibility of a groundwater-sourced water supply for Darfield township within the Racecourse Hill area. Several impermeable layers underlying the Hawkins River were identified and a sketch map of the surface geology produced.

Most recent investigations have not focused on any particular region within the field area but have instead examined the whole Selwyn plains bounded by the foothills, Lake Ellesmere and the Waimakariri and Rakaia rivers. Brown (1974) constructed piezometric contours for the Selwyn plains and mapped the likely availability of groundwater based on aquifer yields. Bowden and Ayrey (1982) investigated the availability of groundwater at different depths, groundwater recharge sources and water quality issues. Donaldson (1977) attempted to distinguish river recharged versus rainfall recharged groundwater within the Selwyn plains based on water level patterns and calculated the likely seasonal input to groundwater from rainfall and the Waimakariri, Rakaia and Selwyn rivers. Cooper (1980) also calculated the likely input to groundwater from the Waimakariri, Rakaia and Selwyn rivers as well as the smaller Selwyn tributaries (Hororata, Waianiwaniwa and Hawkins rivers). A zone of higher transmissivity was identified from well yields immediately adjacent to and south of the Selwyn River.

Moore (1991) examined groundwater levels and well yields within the Greendale area in order to identify key low groundwater levels at which restrictions on groundwater abstractions should apply. A computer model to forecast water levels was also included so that the groundwater resource in that area could be appropriately managed.

The first comprehensive evaluation of the groundwater and surface water resources of the Selwyn plains was performed by Bowden et al (1983). This report included detailed cross-sections, water level interpretation, piezometric contours, groundwater availability maps and a detailed water balance. Anderson (1994) also described the groundwater resources of the Selwyn plains in detail. A groundwater model and a summary of gaugings performed on the Selwyn and Hororata rivers were also included.

The most recent comprehensive report on the water resources of the Selwyn plains is by Taylor (1996). This report was largely a summary of Bowden et al (1983) and Anderson (1994) but also contained updated and new material such as groundwater management zones.

1.7 Research Methods

A postal farmer survey was originally sent to about 80 farmers throughout the field area. The survey asked farmers to identify any wells and springs on their property and to provide any other useful information about problems with groundwater supplies. The return rate was about 60%. This survey proved useful as a starting reference for spring identification and a number of new wells were identified which weren't recorded on the Environment Canterbury wells database.

Field visits to approximately 400 wells were undertaken during the initial stages of the research. The main purpose of these visits were to identify wells which would be suitable for water level monitoring, piezometric surveys and groundwater sampling to be carried out during the research. The majority of visited wells were quality assured to check whether recorded well details were correct and water levels were measured where possible.

Based on initial visits approximately 40 wells were selected for fortnightly manual water level readings and 5 wells were selected for automatic water level recording with groundwater divers. Water levels in these later wells were recorded at 1 hour intervals over several months and data downloaded regularly.

A piezometric survey was undertaken during July 2004 on approximately 130 wells to determine groundwater flow directions in the different aquifers. Well elevations were later surveyed to within less than 0.5m accuracy using a differential GPS.

Concurrent river gaugings on the Selwyn and Hororata rivers were undertaken on 5 different occasions between September and December 2005. A number of different gauging locations were selected to identify gaining and losing reaches.

Chemical sampling of 35 wells and a spring were carried out during February 2005 in order to characterise the groundwater chemistry within the different aquifers and identify sources of groundwater recharge. In addition, 12 wells were sampled for age tracers to characterise the age of groundwater both spatially and with depth and to help restrain groundwater recharge sources.

1.8 Thesis Format

The thesis is presented in seven chapters. Chapter two describes the geology and geomorphology of the Quaternary fan deposits. Chapter three discusses the surface water and spring resources of the area and includes results of river gaugings. Chapter 4 discusses the groundwater resources of the area, identifies aquifers and presents interpretation of water level data carried out during the research. Chapter five presents water chemistry results and interpretation. Chapter six presents findings of groundwater age tracer sampling. A summary of data from chapter two through to chapter six and recommendations for future research are presented in Chapter seven.

Chapter Two

Geology and Geomorphology

2.1 Introduction

This chapter describes the geology and geomorphology of the upper Selwyn Plains. The first section deals mostly with the depositional history of the late Quaternary gravels. A summary of gravel stratigraphy, including descriptions of the various gravel deposits which form the principal water bearing aquifers, is also included. Possible depositional and structural influences on the development of the gravels and their likely effect on the hydrogeology of the region are also discussed.

2.2 Geology

2.2.1 Regional geological setting

New Zealand is located on the edge of two major tectonic plates, the Pacific Plate and the Australian Plate (Figure 2.1). To the south of New Zealand and underneath Fiordland, in the South Island of New Zealand, the two plates are moving obliquely towards each other with the Australian Plate being subducted beneath the Pacific Plate. The two major structures accommodating the stress associated with this tectonic boundary are the Marlborough Fault System (MFS) and the Alpine Fault. Compressional movement along the Alpine Fault has resulting in the formation of the Southern Alps, which are the major topographical feature of the South Island of New Zealand.

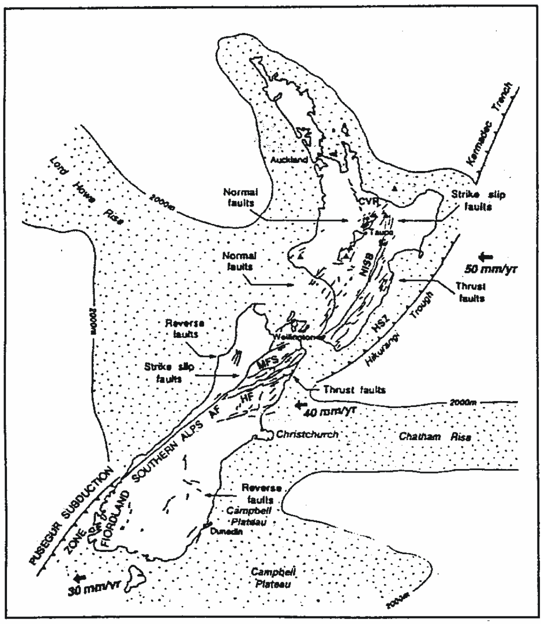


Figure 2.1 New Zealand tectonic plate boundary (from Pettinga and Armstrong, 1998).

2.2.2 Basement rocks

The basement rocks of the Canterbury Plains are Late Paleozoic to Mesozoic in age and consist predominantly of Torlesse Supergroup greywacke (similar to those that make up the Southern Alps) with minor volcanics, chert and limestone (NZGS, 1972). These rocks have experienced two major periods of folding and faulting associated with plate convergence, firstly during the Rangitata Orogeny (about 142 to 99 million years ago) and secondly during the Kaikoura Orogeny (about 24 million years ago to the present) (Suggate et al, 1978). Basement is unconformably overlain by a sequence of Late Cretaceous to mid-Tertiary rocks which include coal measures, sandstone, greenstone, limestone and minor basalt which have been folded since deposition (Brown & Weeber, 1992). Folded and faulted fluvial gravel deposits of the early Quaternary overlie these sediments which are in turn overlain by largely undeformed late Quaternary gravels. Figure 2.2 summarises the geological strata of the Canterbury Plains from the foothills to the coast.

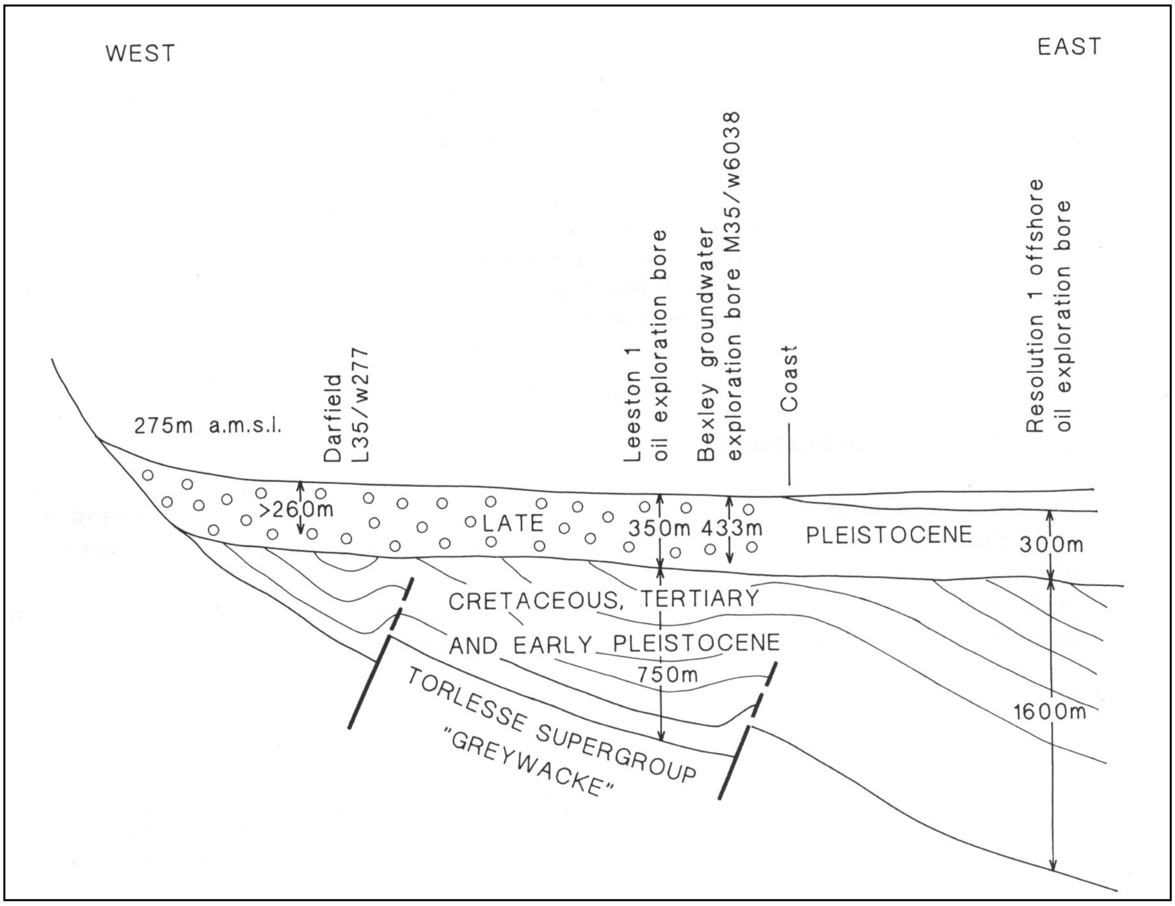


Figure 2.2 Diagrammatic cross-section showing the geological strata of the Canterbury Plains from the foothills (left) to the coast (right). From Brown and Weeber (1992).

2.2.3 Selwyn plains late Quaternary depositional history

The majority of the gravel deposits of the Selwyn Plains were formed during the late Quaternary period (approximately the last 400,000 years) when rapid uplift associated with the Kaikoura Orogeny, combined with glacial erosive processes, resulted in accelerated erosion of the Southern Alps greywacke. The eroded sediment and gravel was transported by east flowing rivers, largely during glacial periods, and deposited on the plains as fans.

Gravel deposition has been greatly affected by climatic changes during the Quaternary. During glacial periods (ice ages) large glaciers occupied the larger Waimakariri and Rakaia river valleys and extended to the eastern edge of the foothills (Brown and Weeber, 1992). During these times erosion rates increased due to reduced vegetation cover on the alps and an increase in mechanical weathering of greywacke by ice, snow and water (Brown, 2000). This resulted in the eastward transport of immense volumes of gravel, sand, and silt from the glacier-fed rivers to form a series of large coalescing outwash fans on the plains. The lateral extent of the Waimakariri and Rakaia fans varied from one glaciation to the next resulting in complex overlapping of the fans. The smaller Selwyn River, with its unglaciated catchment, occupied the depression between the larger Waimakariri and Rakaia outwash fans. Soons (1963) suggested that the Selwyn River acted as a meltwater channel for the Rakaia glacier, with the position of its course varying from one glaciation to the next. A simple sketch of fan structure within the study area is shown in figure 2.3. Sea levels during glacial periods were approximately 120 to 150 metres lower than present and shorelines several kilometres further east (Brown and Weeber, 1992).

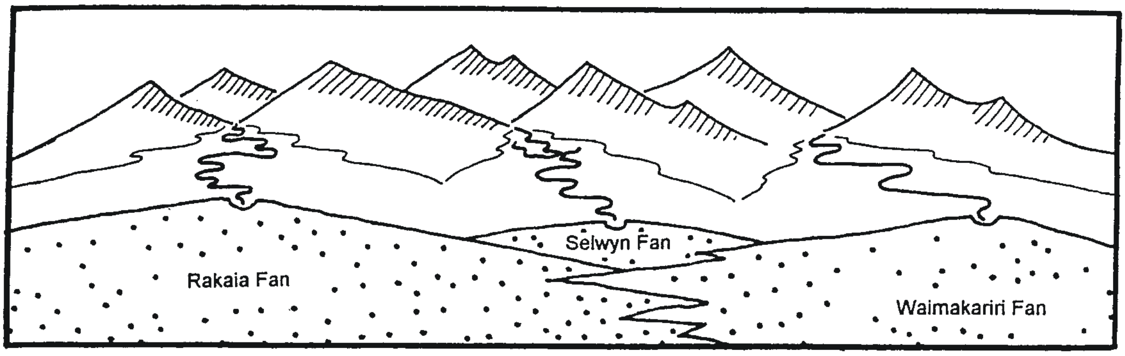


Figure 2.3 Diagrammatic sketch of alluvial fan structure of the Selwyn plains. From Anderson (1994).

During the warmer interglacials and postglacial periods the glaciers retreated, and vegetation re-established to higher altitudes resulting in lower erosion rates and reduced fluvial transport of sediment. This reduced sediment load allowed the Waimakariri and Rakaia rivers, and to a lesser extent the Selwyn River, to entrench into the older glacial outwash deposits in their upper reaches with reworking and transportation of sediment further downstream (Bowden et al, 1983). As sea levels rose, the shoreline moved westwards and fine-grained swamp, estuarine and beach sediments were deposited on glacial outwash gravels near the present day coastline. The repeated rise and fall in sea level accompanying climatic changes has produced an alternating sequence of outwash gravels and fine marine/estuarine sediments near the present-day coastline.

Inland, aquifers are thought to be represented by the more permeable gravels deposited during glacial periods, whilst further towards the coast marine sediments act as aquitards separating the aquifers.

Deep groundwater bores located within the Selwyn plains near Darfield and Te Pirita show that gravels are at least 280 metres thick in the inner plains area. Elsewhere on the Canterbury plains gravel thickness has been recorded in 5 petroleum exploration bores located at Seafield (545m), Brookside (355m), Chertsey (413m), Rangitata (630m) and offshore at the Resolution-1 site (311m), which show that the thickness of alluvial gravels is variable. Variation in gravel thickness may be largely attributed to fan deposition over basement rocks, which are undulating due to intense folding and faulting.

2.3 Stratigraphy

2.3.1 Accepted nomenclature

A number of glacial advances have been recognised within the river valleys of the Waimakariri and Rakaia rivers through the identification of glacial moraines and other morphological features (e.g. Gage, 1958 and Soons, 1963). Over the years the aggradational outwash surfaces associated with these glacial advances have been traced onto the inner plains and a nomenclature to identify the inland plains surface gravels in terms of climatic events determined (e.g. Oborn & Suggate, 1959; Suggate, 1958, 1963, 1965 & 1973). In the coastal region a separate nomenclature, distinct from that of the inner plains, was devised to describe the subsurface lithology of the coastal sediments in terms of glacial stages (Suggate, 1958; Brown & Wilson, 1988).

Although inland plains gravel deposits are recognizable in the field by characteristics such as colour, degree of weathering and sorting, it is almost impossible to extrapolate these units underground because erosion intervals cannot be recognised from bore log descriptions. At the

Table 2.1 Nomenclature and tentative correlations between late Quaternary inland surface deposits and subsurface coastal deposits of the northern Canterbury Plains (modified from Brown & Wilson, 1988).

International Time Divisions			Climatic Event (Suggate 1965 & 1985)	Began Years Ago	Inland Canterbury Surface Deposits (Suggate 1965 & 1973)	Coastal Canterbury Subsurface Deposits (Brown & Wilson 1988)
Period	Epoch					
Quaternary	Holocene		Aranui Postglacial	14,000	Springston Formation	Springston and Christchurch Formations
	Pleistocene	Late Pleistocene[4]	Otira Glaciation	70,000	Burnham Formation[3] / Windwhistle formation[3]	Riccarton Gravel
			Kaihinu Interglacial	120,000	-[1]	Bromley Formation
		Mid Pleistocene[4]	Waimea Glaciation	200,000	Woodlands Formation	Linwood Gravel
			Karoro Interglacial	250,000	-[1]	Heathcote Formation
			Waimaunga Glaciation	310,000	Hororata Formation (part)	Burwood Gravel
			Scandinavia Interglacial	350,000	-[1]	Shirley Formation
			Nemona Glaciation	380,000	Hororata Formation (part)	Wainoni Gravel
		Early Pleistocene[4]	Nukumaruan/Opoitian Glaciations (Andrews et al, 1987)	1,800,000	Kowai Formation	?[2]

Notes:

[1] Deposits not present or unidentified.
[2] Unknown deposits.
[3] Burnham and Windwhistle Formations separated by interstadial event within the Otira Glaciation.
[4] Subdivisions of Pleistocene Epoch based on those of Gradstein, et al (2004).

coast, alternating outwash gravels and finer marine/estuarine sediments allow erosion intervals to be more easily identified from bore log descriptions.

Late Quaternary glacial stages and their formative gravels for both inland and coastal sediments, as suggested by Brown & Wilson (1988), are shown in Table 2.1. Correlations between the inland surface and coastal subsurface formations are tentative because (1) erosion intervals in inland aquifers are impossible to identify (2) coastal deposits are likely to include reworked gravels as well as glacial outwash gravels with marker beds often discontinuous (3) there is a general lack of dateable material to correlate ages. The continuity between inland surface formations and coastal formations is very uncertain.

2.3.2 Inland surface gravel deposits

Inland surface gravel deposits were identified in the field. A brief description of each formation based on Brown and Wilson (1988), Wilson (1989), and work carried out during this study are presented below.

Hororata Formation (ho)

Hororata Formation gravels blanket the southeast slopes of the Harper Hills and Homebush ridge in the upper Selwyn catchment and are the oldest Quaternary deposits within the area. The age of these gravels is uncertain but they have been tentatively correlated with the Waimaunga and Nemona glaciations by Suggate (1965). Exposures are typically comprised of yellow, poorly sorted, coarse and medium gravels consisting of subrounded, friable and highly weathered clasts derived from Torlesse Supergroup greywacke rocks.

Similar gravels capping Racecourse Hill are thought to be correlative to the Hororata Formation (Wilson, 1989). Hororata Formation gravels exposed on Racecourse Hill are shown in figure 2.4. These gravels were highly weathered, very poorly sorted and contained boulders of highly weathered sandstone up to 1m in diameter. The larger clast size can probably be attributed to the close proximity to the foothills and Waimakariri River and could be expected to decrease markedly further towards the coast.

Woodlands Formation (wo)

The Woodlands Formation has been defined by Suggate (1965) as the outwash deposits of the Waimea Glaciation. Typical exposures resemble glacial till and are composed of brown,

Figure 2.4 Typical exposure of Hororata Formation gravels on Racecourse Hill (above) and large boulder of highly weathered sandstone (below).

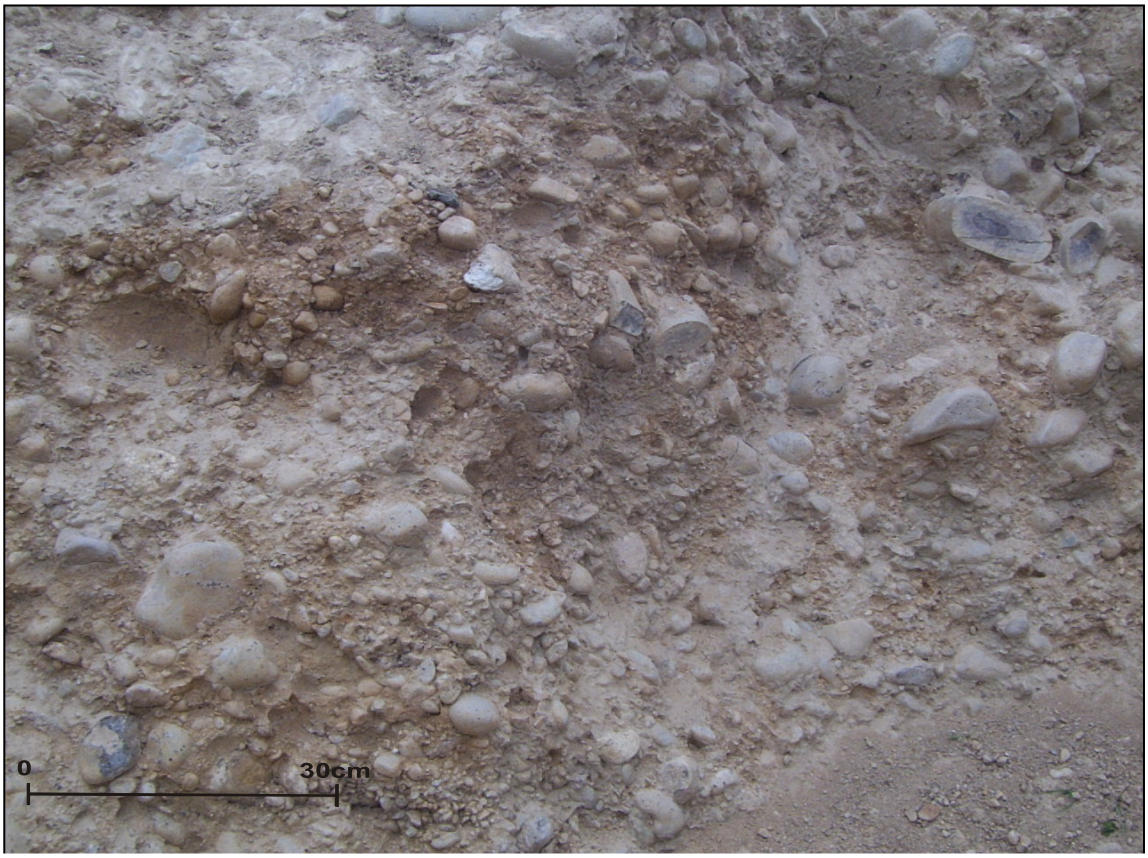


Figure 2.5 Surface exposure of Woodlands Formation gravels (grid reference L35:2302-4057) showing typical morainic appearance.

Figure 2.6 Surface exposure of Windwhistle Formation glacial outwash gravels (grid reference L36:4425-3647).

very poorly sorted, greywacke clasts within a clay/silt/sand/pebbly matrix. A surface exposure of Woodlands Formation gravels along Milnes Road north of the Hororata River (grid reference L35:2302-4057) is shown in figure 2.5.

Windwhistle Formation (le)

The Windwhistle Formation is thought to have been deposited during an early Otiran glacial advance between approximately 40,000 and 70,000 years ago (Brown and Wilson, 1989). Gravels are typically creamy-brown in colour, poorly sorted and composed of dominantly pebble sized clasts within a sand and silt matrix. A surface exposure of Windwhistle gravels derived from the Waimakariri River in the middle of the field area at the corner of Courtenays Road and Telegraph Road (grid reference L36:4425-3647) is shown in figure 2.6.

Burnham Formation (bu)

Burnham Formation gravels were deposited during the Otiran glacial advance between approximately 15,000 and 27,000 years ago (Wilson, 1989) and comprise the last significant outwash laid down as part of the present day plains. Surfaces formed from Burnham Formation (and Windwhistle Formation) gravels are undulate and marked with numerous remnant paleochannels which are mostly absent within the Hororata and Woodlands Formations. Typical exposures are brown in colour and composed of moderately sorted and rounded gravels in a sand and silt matrix. The Burnham Formation is very similar to the Windwhistle Formation but the two can usually be distinguished because the Windwhistle Formation generally has more weathering of the matrix.

A comparison between Burnham Formation gravels derived from the Rakaia and Selwyn rivers was made in the field. Burnham Rakaia gravels (Bu_r) were described from a pit on the corner of Mitchells Road and Hororata-Dunsandel Road (grid reference L36:3133-3309) and Burnham Selwyn gravels (Bu_s) from an old terrace scarp near the Selwyn River (grid reference L35:2783-4393). Overall, Bu_s gravels were slightly better sorted, contained fewer fines (silt, sand) with the matrix constituting a smaller percentage of the overall composition and showed less variation in clast sizes which lead to an appearance of a more permeable gravel. The greater permeability of the Bu_s deposits could be attributed to the unglaciated nature of the Selwyn River catchment. Additionally, the addition of lateral meltwater received from the Rakaia Glacier as suggested by Soons (1963) may have aided in the sorting of gravels. A comparison of Bu_s and Bu_r gravels is shown in figure 2.7.

Figure 2.7 Comparison of Burnham gravels derived from the Rakaia River (above) and the Selwyn River (below). Selwyn River deposits are overlain here by approximately 1m of loess.

Both Burnham gravels derived from the Rakaia River (bu_r) and Windwhistle gravels derived from the Waimakariri River (le_w) contained laterally discontinuous lenses of sand or lenses of dominantly pebble sized clasts with no fines. These lenses probably represent more permeable older remnant surface channels and overbank deposits respectively and are illustrated in figure 2.8.

Springston Formation (sp)

Springston Formation gravels represent the fluvial deposition that followed glacial retreat beginning at the end of the Otiran Glaciation approximately 14,000 years ago. It contains all postglacial fluvial deposits, except those of the present-day river channels and floodplains that are periodically reworked by floods. Gravels can be expected to be of significantly higher permeability than older glacial deposits.

Present-day flood plain deposits (fa)

The youngest gravel deposits comprise the present-day river flood plains. These deposits consist predominantly of rounded, moderately well-sorted, fresh greywacke gravels and sands (Wilson, 1989).

A stratigraphic column describing the different Quaternary gravels of the plains is included with a geological map of the area in figure 2.9 (back pocket).

2.4 Geomorphology

A geological map, modified from that of Wilson (1988), was produced showing the surface distribution of Quaternary gravel formations on the plain and foothills of the upper Selwyn catchment between the Rakaia and Waimakariri rivers (Figure 2.9 – back pocket). Subscripts attached to the formation names indicate the river from which the gravel fans originated. Faults and anticlines were added from Jongens (1999).

Figure 2.9 shows that the Selwyn fan, consisting of gravel deposits from the Selwyn, Hawkins, Hororata and Waianiwaniwa rivers, has an area of approximately 200km^2 and is elongate NW-SE. Near the foothills only remnants of the older Waimea glaciation (Woodlands Formation) and Waimaunga and Nemona glaciations (Hororata Formation) are exposed at the surface.

Figure 2.8 Photos illustrating discontinuous permeable pebble lenses (top and middle) and discontinuous sand lense (below).

Gravel boundaries were distinguished largely by geomorphological features and surface textures through the use of field mapping/observations and aerial photo interpretation. The form and direction of old remnant river channels give critical information about the rivers that formed them. Old surface channels proved particular useful for distinguishing Burnham and/or Windwhistle formation gravels derived from the Rakaia and Waimakariri rivers from Burnham and/or Springfield formation gravels derived from the Selwyn River and its tributaries. Surface morphology of the larger Waimakariri and Rakaia fan deposits show fine-textured channelling reflecting braided rivers "choked" with sediment (figure 2.10). Channel azimuths are consistent with a flow source from the direction of where the major rivers emerge from the foothills, and cut across or are at high angles to the present day courses of the Selwyn fan rivers. In contrast, remnant channels of the Selwyn fan rivers are broader and sinuous reflected a more meandering pattern typical of rivers with a lower sediment load. Channel azimuths of the Selwyn fan rivers, in most instances, are parallel or subparallel to the present courses of the rivers. Differences in channel morphology between Burnham deposits of the Rakaia and Selwyn rivers are illustrated in figure 2.11.

Figure 2.10 Fine textured surface channelling on Rakaia Fan deposits between Rakaia River and Hororata River reflecting a braided river environment.

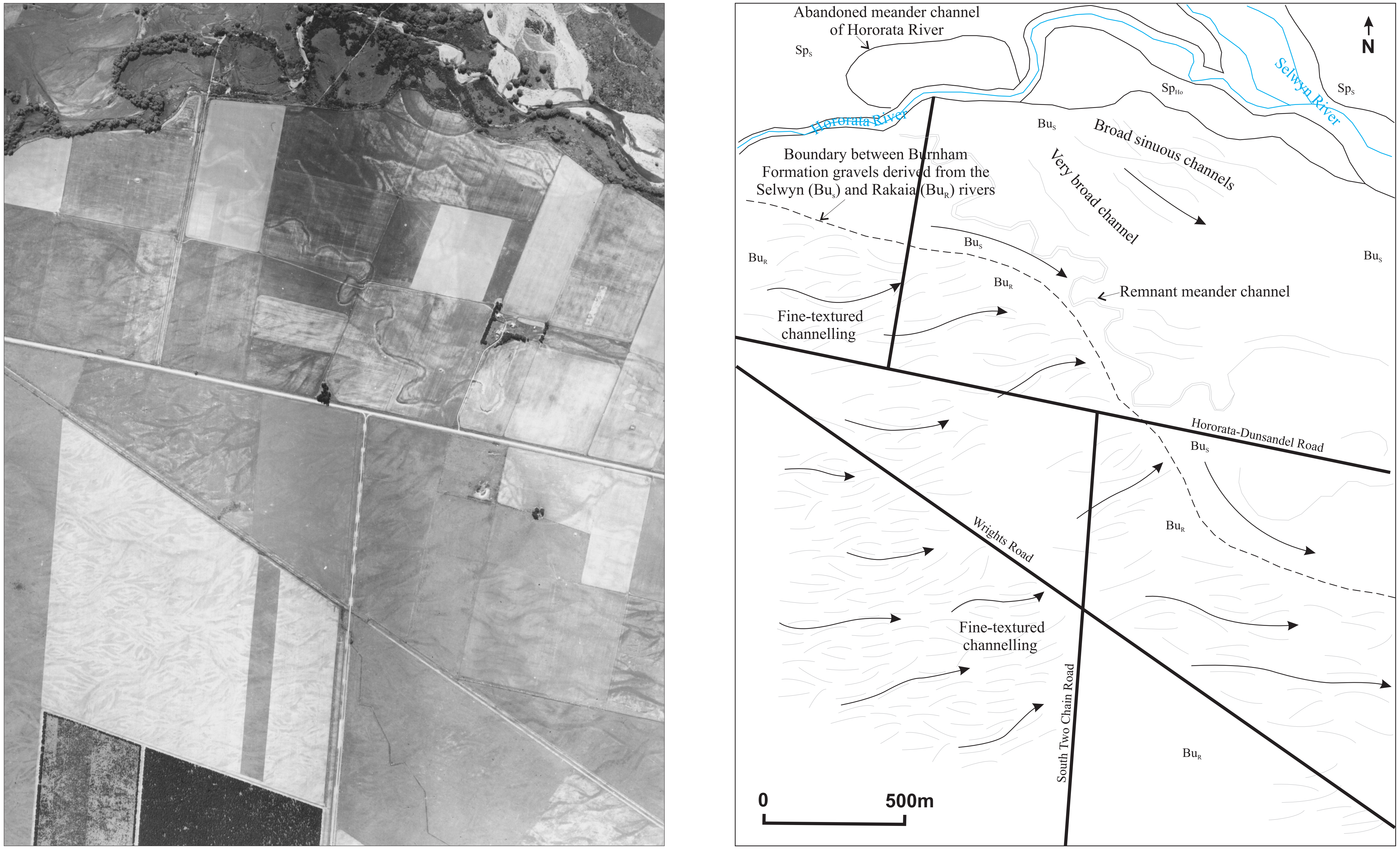


Figure 2.11 Aerial photo with sketch illustrating the difference in textural features of surface channels between Burnham formation gravels derived from the Selwyn River (Bu$_S$) and those derived from the Rakaia River (Bu$_R$). Channels on Rakaia gravels show fine-textured braided river channeling compared to the more broader sinuous meandering nature of Selwyn fan channels. Channel azimuths are shown as arrows.

In addition to surface channel morphology the identification of remnant degradational terraces, produced by downcutting of rivers during interglacial and postglacial periods, was critical as they often defined gravel boundaries.

Black and white aerial photos taken between 1940 and 1943 proved especially useful in identifying terraces and surface textures of remnant channels. This is largely due to the fact that less area within the upper Selwyn plain was farmed at that time. More recently, the increase in total farmed area and intensity of farming practices have obscured many surface features, making identification of terraces and channel textures difficult.

2.5 Influences on the development of the groundwater system

2.5.1 Depositional influences on the hydrogeology

Groundwater movement at depth is likely to strongly reflect the depositional history of the gravel fans that form the aquifers beneath the plains. Progressive shifting and abandonment of river channels on the fan surfaces produced a complex network of interconnected channels of more permeable gravels (i.e. less fines) surrounded by less permeable sediments representing overbank deposits and rapid deposition of gravel sand sill. This pattern can be expected to be retained at depth within the aquifers following burial and preservation of gravels during aggradational events. Lithologically, aquifers can be expected to show local variation in permeability, grain-size and sorting, and it is likely that remnant channels act as preferred flow paths for groundwater.

The surface channel morphology of the different fans is also likely to be reflected at depth. Groundwater within gravel deposits of the larger Waimakariri and Rakaia rivers may be expected to flow through numerous fine remnant braided channels similar to those preserved at the present day surface and similar to those identified in gravel deposits of the Burnham and Windwhistle Formations (figure 2.8). Larger interglacial remnant channels, similar to the present day river courses of the Rakaia and Waimakariri rivers, are not expected within these deposits inland and in close proximity to the Selwyn fan because of the large distance from the main Rakaia and Waimakariri River channels. In contrast, groundwater flow within Selwyn fan deposits probably follows a complex system of smaller channels and broader sinuous remnant meandering channels similar to the present day river channel. A schematic model of the likely hydrogeologic system of the Selwyn plains fans is shown in figure 2.12.

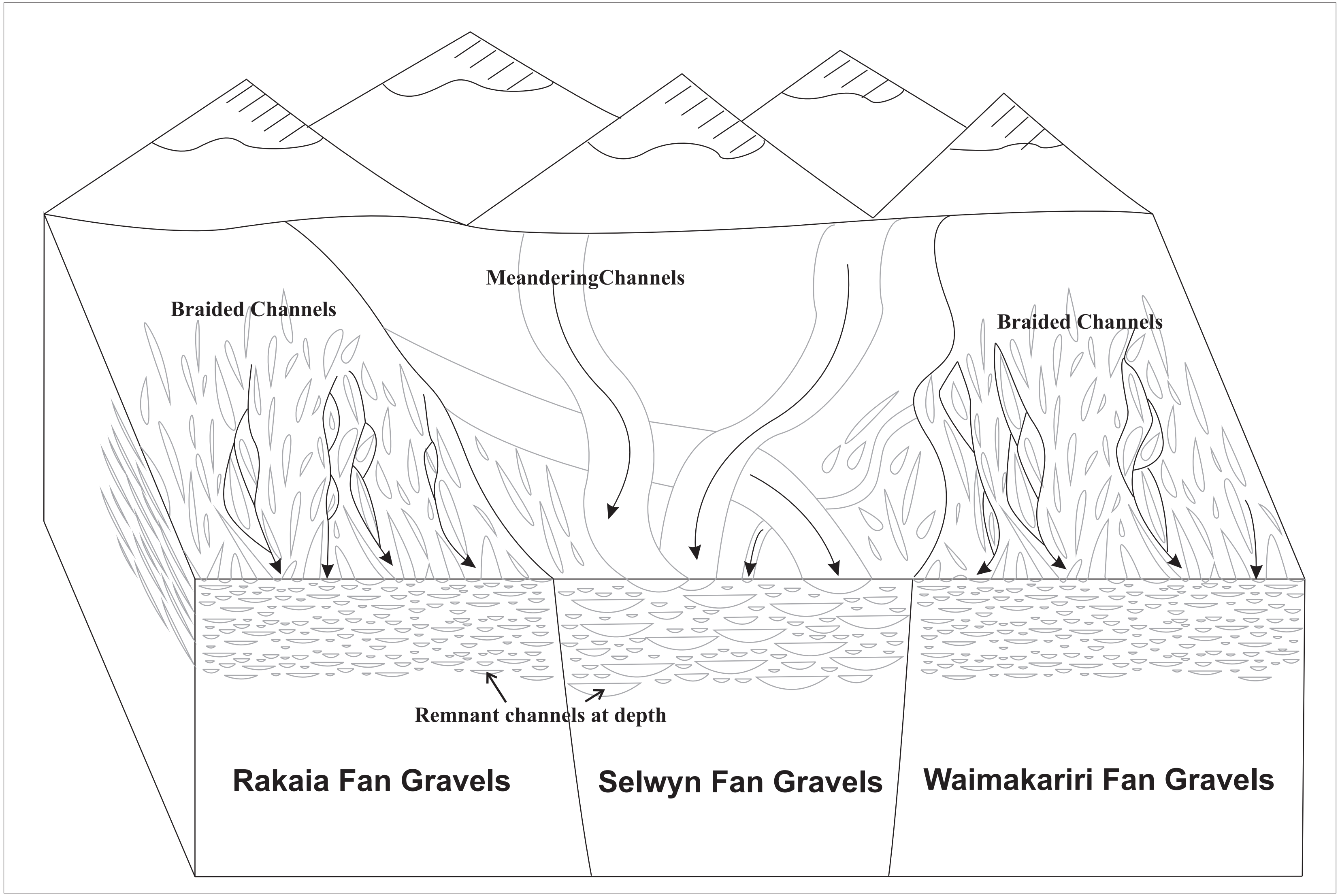


Figure 2.12 Schematic sketch showing likely differences in nature of remnant river channels below the surface. Groundwater within the Rakaia and Waimakariri fan deposits may be expected to flow preferentially through numerous smaller remnant braided channels. In contrast, groundwater within the Selwyn fan deposits may flow preferentially through numerous smaller channels and more sinuous broader channels representing remnant meandering channels.

Sorting can also be expected to have a significant influence on the hydrogeologic system because it is directly related to permeability. In general, sorting increases towards the coast as sediment is reworked and transported downstream. Inland aquifers can be expected to overall be lower yielding than aquifers further towards the coast and with a lower chance of finding a reliable source of groundwater. Glacial deposits derived from the Selwyn River can be expected to locally have a higher degree of sorting and permeability as a consequence of the additional meltwater derived from the Rakaia glacier and the unglaciated nature of the Selwyn Catchment.

Constant shifting of channels of the Selwyn, Hororata, Waianiwaniwa and Hawkins rivers is likely to have created a complex pattern of interweaving and cross-cutting of older remnant channels and overbank deposits within Selwyn fan deposits.

2.5.2 Structural influences on the hydrogeology

2.5.2.1 Hororata Fault

The Hororata Fault (figure 2.9) was first recognised when Indo-Pacific Ltd carried out a seismic reflection survey near Coalgate during the late 1990s. A seismic survey conducted by Finnemore (2001) also identified the presence of the fault near Racecourse Hill.

The Hororata Fault is probably part of a broad zone of deformation related to oblique continental collision and part of a system of thrust faults and related folds that propagate beneath the Canterbury Plains (Pettinga et al, 2001). It is essentially a northwest dipping thrust fault with an associated anticline (Hororata Anticline) some 14km towards the southeast. Both the fault and anticline are blind structures with essentially no visible surface expression. Jongens et al (1999) estimated the fault to have a vertical throw of approximately 800m with deformation commencing in the mid Pleistocene during gravel deposition.

Any activity on this fault during or after Quaternary gravel deposition may be expected to alter the flow regime of local rivers and locally disrupt existing gravel layering at depth thus affecting the flow of groundwater. Ouchi (1985) indicated that meandering rivers, similar to the Selwyn River and its tributaries, may respond to an axis of uplift (i.e. thrust fault propagating at the surface) by developing multiple stable channels in an anastomising pattern on the upstream side of the uplift and a progressive increase in the sinuosity of channels on the downstream side (figure 2.13).

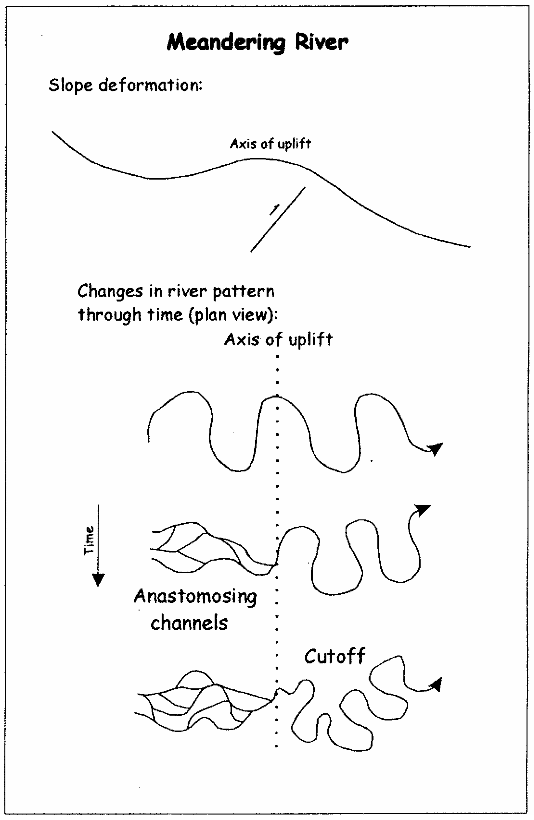


Figure 2.13 Schematic response of meandering river to growth of anticline caused by thrust faulting. From Ouchi (1985).

The Hororata Fault could also possibly act as a preferred path for groundwater flow. Investigations reveal that surface losses to groundwater from the Waianiwaniwa and Hawkins rivers during normal flows approximately coincide with the intersection of the fault with the river channels. Additionally, abandoned channels of the Hororata River near Hororata Township coincide with the intersection of the Hororata Fault with the river which suggests that the Hororata fault has had a recent effect on channel flow.

2.5.2.2 Racecourse Hill

The deposits that form Racecourse Hill (figure 2.14), an approximately 5km^2 hilly area 6km north of Darfield, have been described as remnant Hororata Formation gravels left behind by the Waimauanga and/or Nemonian glacial advances. Borelogs within nearby wells on the upthrown side (northwest) of the Hororata Fault describe the presence of Tertiary like glauconitic or quartz sands at varying depths whilst wells on the downthrown side (southeast) describe the presence of gravels down to a depth of at least 255m. The location of these wells is shown on figure 2.9 and borelogs in appendix 2.1. The presence of Tertiary sediments indicates that significant uplift of foothills sediments has occurred to the northwest of the Hororata Fault near Racecourse Hill contemporaneous with gravel deposition. Racecourse Hill is likely to be an uplifted fault block of Tertiary sediment capped by a thin veneer of Hororata Formation gravels.

Depending on the lateral and vertical extent of reasonably impermeable Tertiary deposits at depth Racecourse Hill can be expected to locally act as a significant barrier southeastward to groundwater flow.

Figure 2.14 Racecourse Hill looking from the northwest.

2.6 Summary

Gravel deposits derived from the Rakaia, Waimakariri and Selwyn rivers were identified from field observations and aerial photographs and a map produced showing their surface extent. Burnham Formation gravels derived from the Rakaia River and Windwhistle Formation gravels derived from the Waimakariri River are extensive, and occupy much of the surface plains between the Rakaia and Hororata rivers and Waimakariri and Hawkins rivers respectively.

Surface channel morphology between glacial Burnham gravels derived from the Selwyn River and those derived from the Rakaia and Waimakariri rivers are different. Surface channel morphologies of the Rakaia and Waimakariri rivers are typically fine-textured reflecting large braided river environments. In contrast, surface channelling in Selwyn River Burnham deposits are typically broader and more sinuous reflective of a meandering river system. Differences between channel morphologies were critical in identifying surface gravels derived from the different rivers.

Channel morphology at the surface is likely to be reflected at depth. Groundwater is likely to flow preferentially through numerous small permeable remnant channels within Rakaia and Waimakariri glacial deposits, and through smaller and broader sinuous channels at depth within Selwyn Fan deposits.

The Hororata Fault coincides with river losses during normal flows within the Hawkins and Waianiwania rivers and is likely to have had a significant effect on the development of the groundwater system within the field area. Racecourse Hill is likely to be an uplifted block of Tertiary sediment capped by a thin veneer of Hororata Formation gravels and can be expected to locally have a significant effect on groundwater flow.

Chapter Three

Surface Hydrology and Springs

3.1 Introduction

An understanding of surface waters and springs, particularly their occurrence, flow, characteristics and seasonal and long term fluctuations is critical in establishing a comprehensive understanding of the hydrogeology of a region because surface water and groundwater resources are often connected.

Previous studies within the field area (e.g. NCCB, 1983 and Anderson, 1994) have highlighted the importance of river leakage from the Selwyn River as a significant recharge mechanism to groundwater.

This chapter combines information from previous research with surface water investigations carried out during the course of this study (including river gaugings on the Hororata and Selwyn rivers and the identification of springs) to obtain a better understanding of surface water and groundwater interactions within the field area.

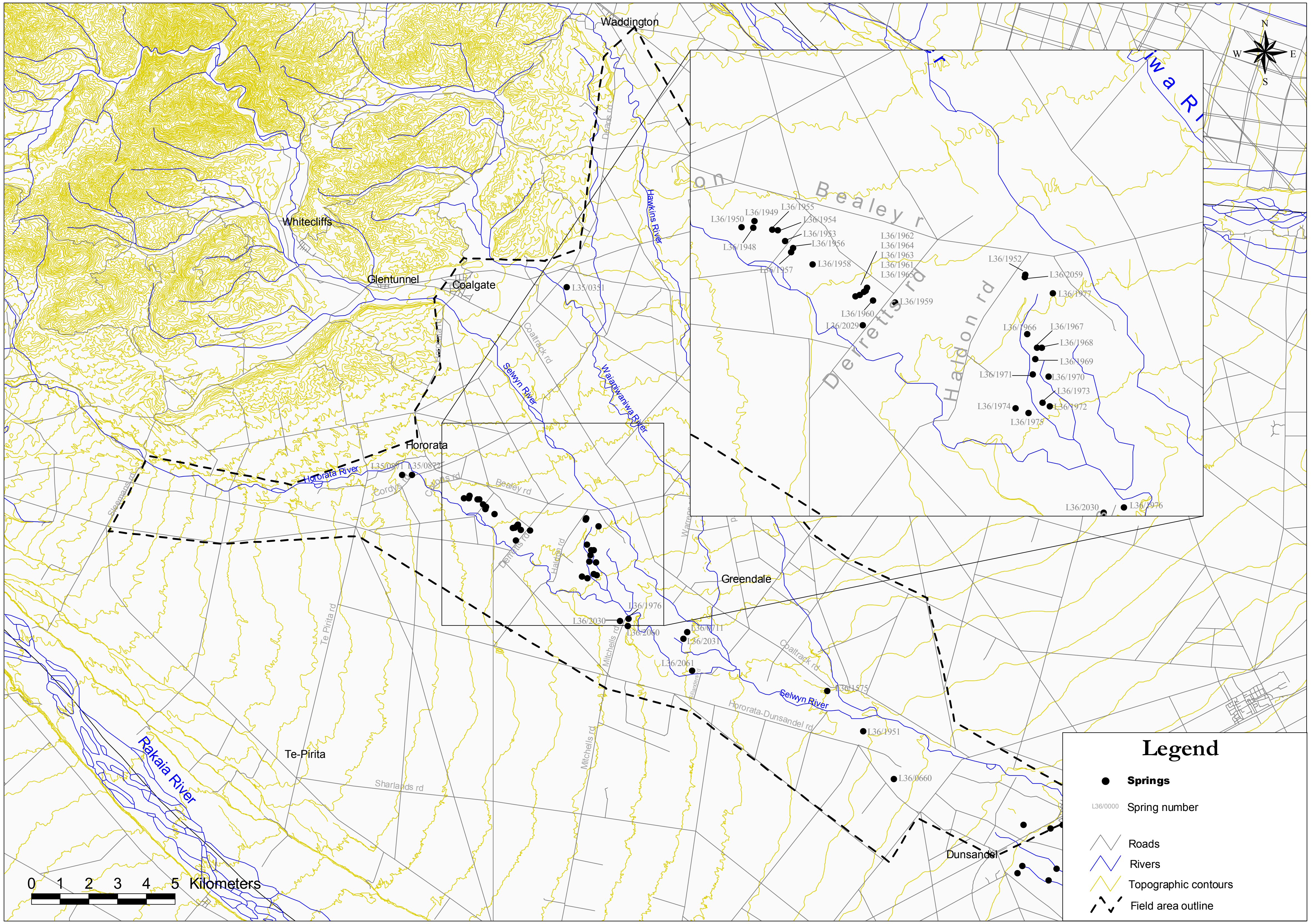
3.2 Springs

3.2.1 Spring identification and classification

Prior to this study only five springs within the field area had been identified and recorded within Environment Canterbury's spring database. Approximately 40 further springs were identified during the course of this study (figure 3.1). Springs identified in the field were assigned numbers and their location recorded with a hand-held GPS where possible. Figure 3.1 shows that the majority of springs outcrop within two distinct belts between the upper reaches of the Selwyn and Hororata rivers. One belt of springs is orientated NW-SE and located several hundred metres north of the Hororata River between Cotons Road and Derretts Road. The other belt of springs is orientated N-S and located approximately one kilometre east of Haldon Road.

Springs were classified by spring type (depression, contact, artesian, fault, joint/fracture or sinkhole), spring morphology (seepage, point source, linear/channel or horizon), discharge

Figure 3.1. Springs within the upper Selwyn Plains



variability (permanent, intermittent, unknown) and geology type (gravels, sands, silt, mud, soil or other). A description of spring classification criteria and illustrations of spring types and their morphology are included in Appendix 3.1.

A summary of identified springs and their classification is shown in Table 3.1. Table 3.1 shows that the majority of springs within the field area are depression springs with no observable discharge source (seepage morphology) that occur within gravel deposits with varying proportions of sand, silt and mud. Photos and brief descriptions of several springs are shown in figure 3.2.

3.2.2 Spring source

Spring discharge (permanent versus intermittent) combined with visual observations of spring-fed stream flow and river flows proved useful in identifying the likely recharge sources for the various springs. All springs within the Haldon Road area and springs L36/0711, L36/2031, L36/1575, L36/1951 and L36/0660 (figure 3.1) further downstream, are intermittent in nature. These springs begin flowing shortly after any sustained surface flow within nearby reaches of the Selwyn River, which generally runs dry several kilometres upstream shortly after it emerges from the foothills. Additionally, water levels in nearby shallow wells significantly increase following nearby surface flow events.

It appears that the likely source for these springs is groundwater derived from losses in nearby reaches of the Selwyn River with spring flow dependant on the accompanying rise of the water table. Flow within most of these springs was maintained for approximately 2 to 3 months following surface flow.

Similarly, discharge rates within intermittent springs L35/0871, L35/0872, L36/1976, L36/2030, L36/2060 and L36/2061 (figure 3.1) correlate strongly to flows within the nearby Hororata River. These springs are likely to be sourced from groundwater derived from losses from the Hororata River.

In contrast, all springs between Cotons Road and Derretts Road flowed permanently during the duration of field visits (between April 2004 and September 2005) and local residents commented that these springs have gone dry perhaps only once or twice during the last 60 years. These observations suggest a more permanent source of groundwater for these springs. The likely

Spring number	Spring type	Spring morphology	Discharge variability	Geology type
L35/0871	Depression	Seepage/Point-source	Intermittent	Gravel
L35/0872	Depression	Seepage/Point-source	Intermittent	Gravel
L36/1950	Depression	Seepage	Permanent	Gravel
L36/1949	Depression	Seepage	Permanent	Gravel + Soil
L36/1948	Depression	Seepage	Permanent	Gravel
L36/1955	Depression	Seepage	Permanent	Gravel + Mud
L36/1954	Depression	Seepage	Permanent	Gravel + Mud
L36/1953	Depression	Seepage	Permanent	Gravel + Mud
L36/1957	Depression	Seepage	Permanent	Gravel + Soil
L36/1956	Depression	Seepage	Permanent	Gravel + Soil
L36/1958	Depression	Point-source	Permanent	Gravel + Soil
L36/1962	Depression	Seepage	Permanent	Gravel + Soil
L36/1964	Depression	Seepage	Permanent	Gravel + Soil
L36/1963	Depression	Seepage	Permanent	Gravel + Soil
L36/1961	Depression	Point-source	Permanent	Gravel + Sand
L36/1965	Depression	Seepage	Permanent	Gravel + Soil
L36/1960	Depression	Point-Source	Permanent	Gravel
L36/1959	Depression	Channel/Linear	Permanent	Gravel + Silt
L36/2029	Depression	Seepage	Permanent?	Gravel + Silt
L36/1952	Depression	Seepage	Intermittent	Gravel + Silt
L36/2059	Depression	Seepage	Intermittent	Gravel + Silt
L36/1977	Depression	Channel/Linear	Intermittent	Gravel + Soil
L36/1966	Depression	Horizon	Intermittent	Gravel + Soil
L36/1967	Depression	Point-source	Intermittent	Gravel + Soil
L36/1968	Depression	Seepage	Intermittent	Gravel + Soil
L36/1969	Depression	Seepage	Intermittent	Gravel + Soil
L36/1971	Depression	Seepage	Intermittent	Gravel + Soil
L36/1970	Depression	Seepage	Intermittent	Gravel + Soil
L36/1973	Depression	Seepage	Intermittent	Gravel + Soil
L36/1972	Depression	Seepage	Intermittent	Gravel + Soil
L36/1974	Depression	Seepage	Intermittent	Gravel + Soil
L36/1975	Depression	Seepage	Intermittent	Gravel + Soil
L36/2030	Depression	Seepage	Intermittent	Gravel + Mud
L36/1976	Depression	Seepage	Intermittent	Gravel + Mud
L36/2060	Depression	Seepage	Intermittent	Gravel + Mud
L36/2031	Depression	Seepage	Intermittent	Gravel + Silt
L36/0711	Depression	Seepage	Intermittent	Gravel + Silt
L36/2061	Depression	Seepage	Intermittent	Gravel
L36/1575	Depression	Seepage	Intermittent	Gravel
L36/1951	Depression	Seepage/Point-source	Intermittent	Gravel
L36/0660	Depression	Seepage/Point-source	Intermittent	Gravel
L35/0351	Fault?	Seepage	Intermittent	Gravel

Table 3.1 Summary of Spring type, morphology, discharge variability and geology.

A.

B.

C.

Figure 3.2 Springs within the upper Selwyn plains (A) Typical depression spring (B) Horizon spring near Haldon Road with visible seepage from gravels into spring-fed creek (C) Point source morphology with visible groundwater flow from spring bed.

source is groundwater derived from losses from the Selwyn River shortly after its emergence from the foothills at Coalgate where river flow is permanent. This source is also supported by piezometric contours (section 4.5) and water chemistry (section 5.7.3). River gaugings suggest these springs receive little or no groundwater derived from losses from the Hororata River.

Although most springs appear to be sourced from groundwater derived from surface losses from the Selwyn or Hororata rivers it is likely that they are also significantly affected by rainfall.

3.2.3 Spring origin

Most springs occupy topographic lows and appear to be created by the intersection of the water table with the ground surface (depression type springs). Springs between Cotons Road and Derretts Road especially occur within a pronounced topographic depression at the surface. Borelog descriptions for many wells within close proximity to springs show the presence of thin discontinuous layers of clay or claybound gravel at varying depths. The presence of these layers suggest that groundwater within some springs is also being forced to the surface upon intersection with less permeable clay layers at depth.

3.3 Rivers

The major surface water resources on the upper Selwyn plains between the Waimakariri and Rakaia rivers, include the Selwyn River and its three tributaries the Hororata, Waianiwaniwa and Hawkins rivers. All four rivers are ephemeral in nature and generally run dry soon after their emergence onto the plains.

Continuous flow records have been recorded for the Selwyn River at Whitecliffs since May, 1964. The Whitecliffs recorder site is approximately 3.5km inland from where the Selwyn River emerges onto the plains at Coalgate and is shown in figure 3.3. Flow records between 1964 and 1993 show that high flows usually occur during August and September and low flows during January and February but with considerable seasonal variation (figure 3.4).

3.3.1 River gaugings

During the course of this research the Selwyn and Hororata rivers were gauged concurrently during five different occasions between September and December, 2004 to evaluate losses to and/or gains from the groundwater system. The Selwyn River was gauged at eight different

Figure 3.3 Water level recorder on the Selwyn River at Whitecliffs.

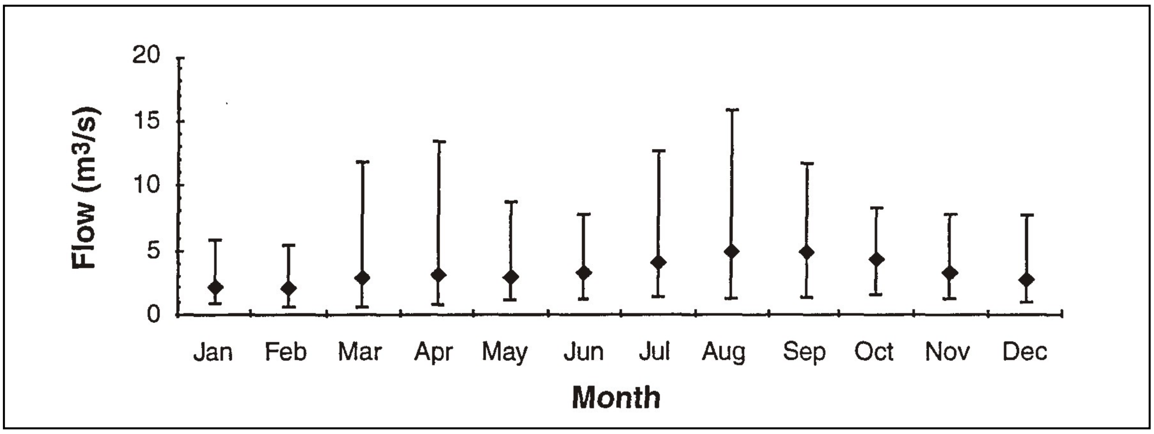


Figure 3.4 Maximum, minimum and mean monthly flows for the Selwyn River at Whitecliffs (from Anderson, 1994).

locations between Whitecliffs and Dunsandel whilst the Hororata River was gauged at six different locations between Sleemans Road and its covergence into the Selwyn River (figure 3.5). Not all locations were gauged during each gauging run because the rivers were not always flowing at those locations and some gauging runs on the Selwyn River were conducted over two days because of time restrictions. The Waianiwaniwa and Hawkins rivers were not gauged during this study.

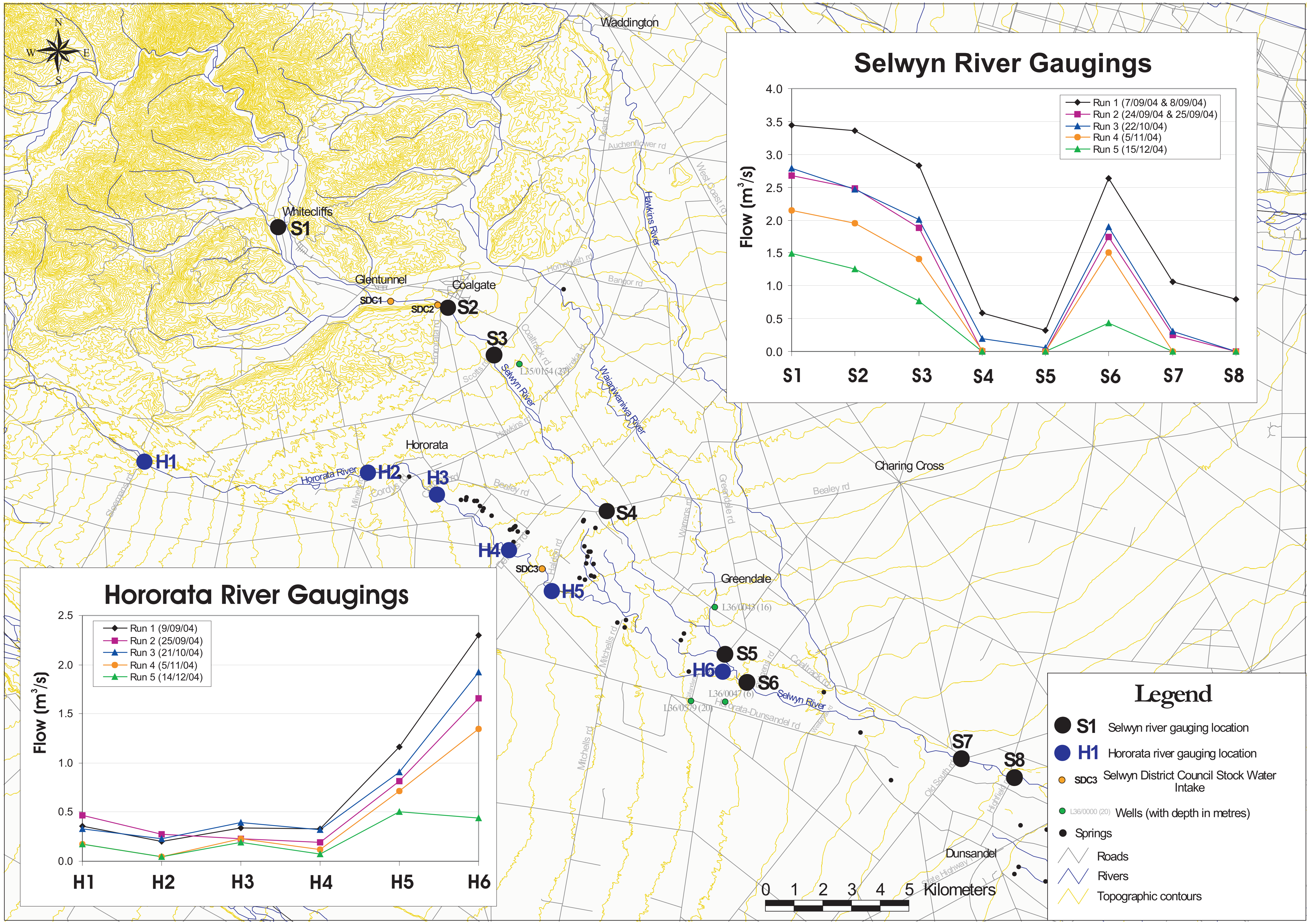
In addition to river gaugings, visual flow observations at a variety of river, spring and creek localities were recorded approximately every two weeks over a one year period between June 2004 and May 2005. Observations for the Selwyn, Hororata, Waianiwaniwa and Hawkins rivers are shown in Appendix 3.2.

3.3.1.1 Gauging methodology

Gauging sites were selected where the river course flowed through a single straight channel with little flow turbulence and which was devoid of any vegetation, rocks and other obstacles that may have adversely affected flow readings. A typical gauging site location is shown in figure 3.6. Gaugings were conducted with a NIWA (National Institute of Water and Atmospheric Research) current metre and a small horizontal axis Ott propeller. At least twenty flow velocity readings were recorded along the length of each channel cross-section at 0.6m of the water depth. Flow rates were calculated by the velocity-area method using the gauging calculation software glog.

Figure 3.6 Gauging site along the Hororata River at Cotons Road

Figure 3.5 Gauging results and locations for the Selwyn and Hororata rivers



3.3.2 Selwyn River gauging results and interpretation

Gauging results for the Selwyn River are shown in figure 3.5 and Appendix 3.3. Gains and losses in river flow between the various gauged reaches are shown in Table 3.2. River abstractions from Selwyn District Council (SDC) stock water intakes at Glentunnel and Coalgate (figure 3.5) were factored into these later calculations.

Gauging Run	Flow at Whitecliffs (S1)	Net losses (-) and gains (+)						
		S2	S3	S4	S5	S6	S7	S8
1	3.44 m^3/s	+ 0.17	- 0.53	- 2.26	- 0.26	+ 2.31	- 1.58	- 0.26
2	2.67 m^3/s	+ 0.05	- 0.59	- 1.89	0.0	+ 1.75	- 1.50	- 2.50
3	2.79 m^3/s	- 0.07	- 0.46	- 1.81	- 0.15	+ 1.85	- 1.59	- 0.31
4	2.14 m^3/s	+ 0.06	- 0.55	- 1.39	- 0.01	+ 1.50	- 1.50	0.0
5	1.49 m^3/s	+ 0.03	- 0.50	- 0.76	0.0	+ 0.44	- 0.44	0.0

Table 3.2 Losses and gains between reaches of the Selwyn River (m^3/s).

Results showed that on all but the third gauging run flows within the Selwyn River slightly increased between Whitecliffs (S1) and Coalgate (S2). Increases between theses reaches are most probably derived from the drainage of nearby foothills creeks into the Selwyn River. Between Coalgate (S2) and Scotts Road (S3) the Selwyn began to lose a significant proportion of its flow to groundwater (between 16% and 40% of its flow at Coalgate) whilst between Scotts Road (S3) and Bealey Road (S4) all or most of its remaining flow is lost (between 60% and 76% of its flow at Coalgate). When the river was flowing only small losses occurred between the Bealey Road (S4) and Gillanders Road (S5) reaches (between 0.5% and 8% of the flow at Coalgate). At Ridgens Road (S6) flow within the Selwyn resumed again as water from the Hororata River was added. Downstream from Ridgens Road (S6) the Selwyn rapidly lost flow to groundwater with most losses occurring between Ridgens Road (S6) and Old South Road (S7) (between 60% and 100% of its flow at Ridgens Road).

In general, surface losses and the downstream extent of flow within the upper reaches of the Selwyn River can be correlated to shallow water table conditions. This is illustrated in figure 3.7 which shows flow records for the Selwyn River at Whitecliffs, flow observations at Bealey Road between June 2004 and June 2005 and water levels in well L35/0154, a 27m deep well located approximately 500 metres east of the Selwyn River near Scotts Road (figure 3.5). Figure 3.7 and visual observations show that on the 30th March 2005 and the 3rd May 2005 flow peaks of

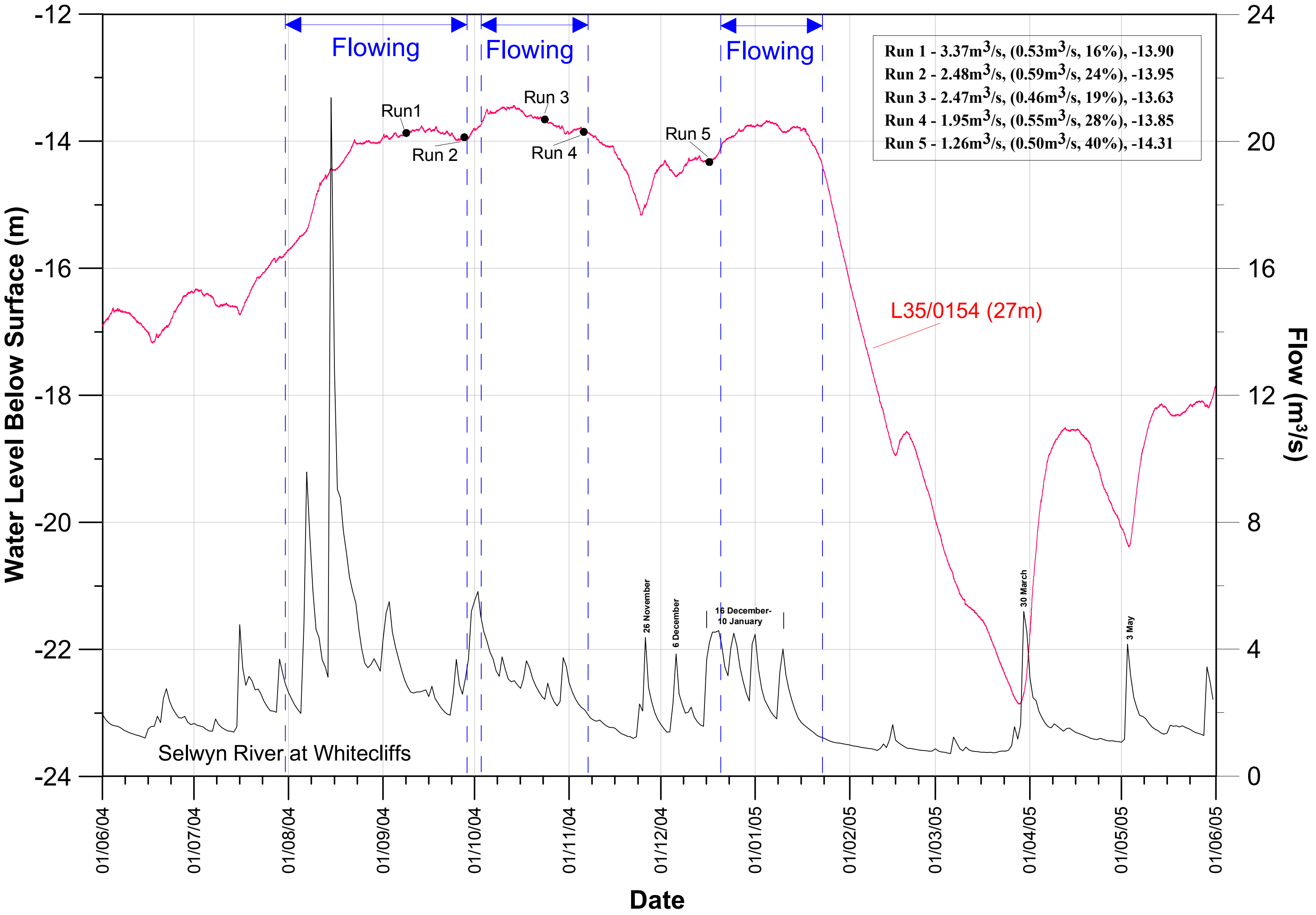


Figure 3.7 Flow at Whitecliffs and water level data for well L35/0154 between June 04 and June 05. Approximate periods of surface flow at Bealey Road are shown as blue dashed lines. Gauging runs with total flow at Coalgate (with losses between Coalgate and Scotts Road and percentage of total flow at Coalgate lost between Coalgate and Scotts Road) and water levels in L35/0154 during time of gauging are shown top right corner.

approximately 5.2m^3/s and 4.2m^3/s respectively were quickly lost to groundwater between Coalgate and Hawkins Road when water levels in L35/0154 were low but losses during gauging runs, which were conducted when shallow water levels were significantly higher and more settled, are much lower with the Selwyn often flowing beyond Bealey Road. Taylor (1996) estimated that surface losses of up to 10m^3/s are possible between Whitecliffs and Bealey Road during periods of low groundwater levels. The rapid rise in water level following the flow peaks of March 30 and May 3 show that the Selwyn River has a significant effect on shallow water levels in its upper reaches and losses during sustained surface flow events and low water tables would rapidly diminish as the shallow aquifer is replenished. The effect of river losses from the Selwyn River on groundwater levels is covered thoroughly in Chapter 4.

Furthermore, river observations at Bealey Road (S4) combined with Whitecliffs flow records show that sustained higher flows or closely spaced lower duration higher flows are required at Whitecliffs for the Selwyn River to flow at Bealey Road. This is also illustrated in figure 3.7. The Selwyn River did not flow at Bealey Road during single peaks of higher flow events on 26 November 2004, 6 December 2004, 30 March 2005 and 3 May 2005 but did flow at Bealey Road during a sustained period of similar magnitude flow events between 16 December 2004 and 10 January 2005. Water levels in well L35/0154 were higher during the period when the Selwyn was flowing at Bealey Road (i.e. between 16 December 2004 and 10 January 2005) and this would suggest a direct correlation between flow at Bealey Road and higher shallow water levels. However, the Selwyn River also flowed at Bealey Road from the end of July 2004 until the end of September 2004. Water levels during the start of this period were lower than those of 26 November 2004 and 6 December 2005 where no flow was present at Bealey Road. Furthermore, when river losses between Coalgate (S2) and Scotts Road (S3) for each gauging run are plotted against water levels at L35/0154 (figure 3.7) it can be seen that there is not a straight forward correlation between losses along these reaches and water level conditions i.e. during gauging run 4, when total flow at Coalgate was 1.95m^3/s and water levels in L35/0154 were -13.85m, more losses occurred to groundwater between Coalgate and Scotts Road than during gauging run 1, where total flow was considerably more (3.37m3/s) and water levels were lower (-13.90m). Overall, results show that surface losses within the upper reaches of the Selwyn River during high flow peaks are greater when shallow water levels are lower with all flow often rapidly lost before Hawkins Road. However, during higher and more settled water levels, a complex combination of total flow within the Selwyn River, duration of flow and shallow water level conditions dictate the amount of losses from the Selwyn River to groundwater in its upper reaches between Coalgate and Scotts Road.

River losses between Ridgens Road (S6) and Old South Road (S7) for each gauging run were similarly plotted against shallow water levels in well L36/0047, a 6m deep well located approximately 700 metres south of the Selwyn River opposite Ridgens Road (figure 3.5), and are shown in figure 3.8. Figure 3.8 shows that the lowest percentage of total flow of the Selwyn at Ridgens Road was lost between Ridgens Road and Old South Road during gauging run 1 (60%), where water table conditions were highest, than during all other gauging runs where water levels were lower. This would suggest that losses between Ridgens Road and Old South Road are related to water table conditions. However, greater losses occurred between Ridgens Road and Old South Road during gauging run 3, when total flow at Ridgens Road was significantly lower (1.90m^3/s), than during gauging run 1 when total flow at Ridgens Road was higher (2.63m^3/s). The greater losses during gauging run 3 could be attributed to the lower water table at that time. Overall, results show a general correlation between surface losses to groundwater and water table conditions in the Selwyn River in its lower reaches between Ridgens Road and Dunsandel.

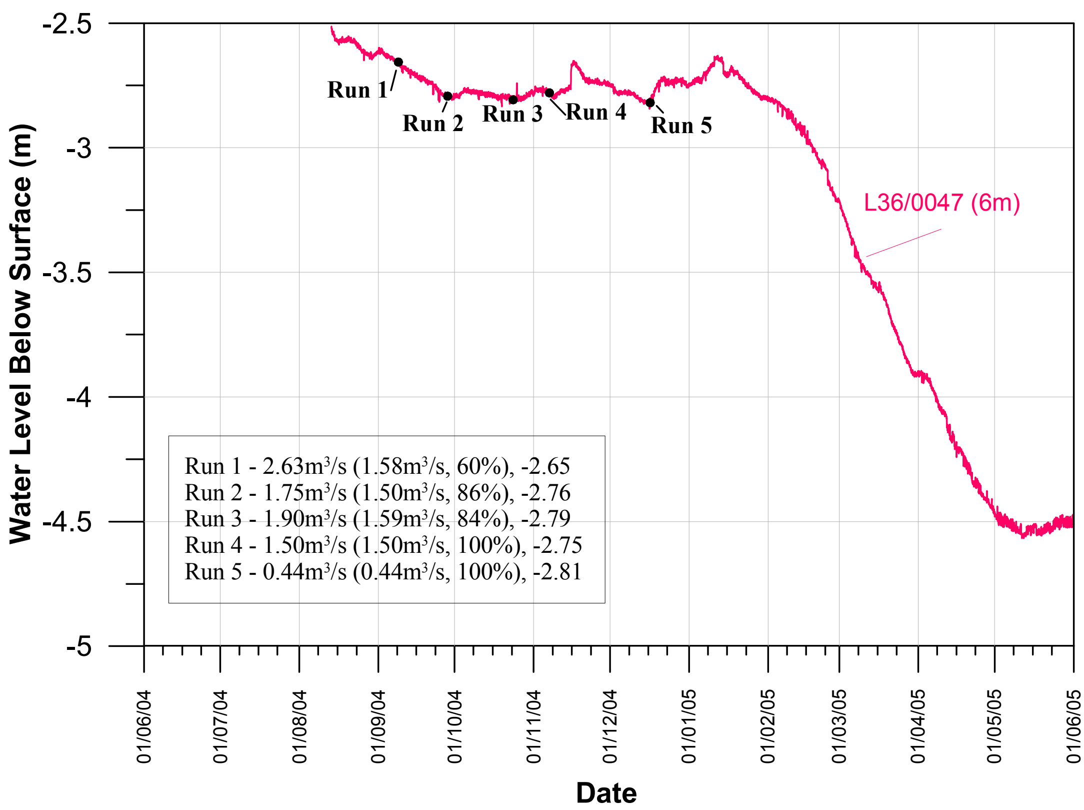


Figure 3.8 Water level data for well L36/0047 and location of gauging runs. Gauging runs with total flow at Ridgens Road (with losses between Ridgens Road and Old South Road and percentage of total flow at Ridgens Road lost between Ridgens Road and Old South Road) and water levels in L36/0047 during time of gauging are shown in bottom left hand corner.

All flow gaugings were conducted during a period when flows within the Selwyn River were reasonably high. The river flowed at Bealey Road for approximately 4months out of the 12months the river was monitored. Anderson (1994) suggested that during a typical season the Selwyn River runs dry and loses all it flow to groundwater soon after Scotts Road for approximately 90% of the year. Pictures illustrating variations in flow at different reaches of the Selwyn River are shown in figure 3.9.

3.3.3 Hororata River gauging results and interpretation

Gauging results for the Hororata River are shown in figure 3.5 and Appendix 3.3. Gains and losses in river flow between the various gauged reaches are shown in Table 3.3. River abstractions from a Selwyn District Council (SDC) stock water intake 500m upstream of Haldon Road (figure 3.5) were factored into these later calculations.

Gauging Run	Flow at Sleemans Road (H1)	Net losses (-) and gains (+)				
		H2	H3	H4	H5	H6
1	0.35 m^3/s	- 0.15	+ 0.14	- 0.01	+ 0.92	+ 1.14
2	0.47 m^3/s	- 0.19	- 0.05	- 0.03	+ 0.72	+ 0.84
3	0.33 m^3/s	- 0.10	+ 0.16	- 0.07	+ 0.72	+ 1.01
4	0.18 m^3/s	- 0.13	+ 0.19	- 0.12	+ 0.73	+ 0.63
5	0.17 m^3/s	- 0.13	+ 0.15	- 0.13	+ 0.57	- 0.70

Table 3.3 Losses and gains between reaches of the Hororata River (m^3/s).

Results show that the Hororata River loses flow ($0.1m^3/s$ to $0.2m^3/s$) between Sleemans Road (H1) and Milnes Road (H2) as it flows parallel to the foothills. It is likely that most of these losses occur close to Milnes Road and act as the source for groundwater recharge to springs L35/0871 and L35/0872 just before Hororata Township. On all but gauging run 2 the Hororata River then gained in flow ($0.1m^3/s$ to $0.2m^3/s$) between Milnes Road (H2) and Cotons Road (H3). The gains in flow between these two reaches approximately match the losses between Sleemans Road and Milnes Road and the likely source is the addition of streams that drain springs L35/0871 and L35/0872. Between Cotons Road (H3) and Derretts Road (H4) the Hororata River then loses flow once more to groundwater but these losses are very small ($0.01m^3/s$ to $0.13m^3/s$). From Derretts Road (H4) to the Selwyn confluence (H6) the Hororata River then rapidly gained in flow. The source for the increase in flow downstream from Derretts

A.

D.

G.

B.

E.

H.

C.

F.

I.

Figure 3.9. Flow along the Selwyn River (A) Typical flow at Whitecliffs, S1 (B) Typical flow at Coalgate, S2 (C) Typical flow at Scotts Road, S3 (D) Flow at Bealey Road, S4(E) Bealey Road when dry (F) Flow at Gillanders Road, S5 (G) Flow at Ridgens Road after the addition of Hororata River water, S6 (H) Flow at Highfield Road, S8 (I) Highfield Road when dry.

Road is the addition of numerous spring-fed creeks derived from losses from the Selwyn River. Spring-fed creeks draining into the Hororata River are shown in figure 3.10.

In general, the magnitude of flow gains downstream from Derretts Road during gauging runs proportionally match the magnitude of losses from the Selwyn River between Coalgate and Gillanders Road (Table 3.4). Visual observations of flow in the Hororata River at the Selwyn confluence (H6) show that flow peaks generally occur several days after peak flows within the Selwyn River at Whitecliffs. This time difference between flow peaks can be attributed to groundwater travel times between the two rivers

Gauging Run	Losses from Selwyn River between S2 and S5	Gains in Hororata River between H4 and H6	Difference
1	-3.05 m^3/s	+1.97 m^3/s	-1.08 m^3/s
2	-2.48 m^3/s	+1.47 m^3/s	-1.01 m^3/s
3	-2.42 m^3/s	+1.60 m^3/s	-0.82 m^3/s
4	-1.95 m^3/s	+1.22 m^3/s	-0.73 m^3/s
5	-1.26 m^3/s	+0.36 m^3/s	-0.90 m^3/s

Table 3.4 Total losses from the Selwyn River between Coalgate (S2) and Gillanders Road (S5) and total gains in the Hororata River between Derretts Road (H4) and the Selwyn confluence (H6).

Water levels in shallow wells L36/0579 (20m deep) and L36/0047 (6m deep), immediately south of the Hororata River (figure 3.5), increase during times of high flows within the river in the absence of significant rainfall. This suggests that the Hororata River also loses significant flow to the shallow aquifer southwards along its lower reaches in addition to the gains it receives from spring-fed creeks. Additionally, during gauging run 5 small losses occurred between Haldon Road and the Selwyn confluence. Figure 3.8 shows that shallow water levels were lower at this time than during the other gauging runs and this suggests that losses from the Hororata River are dependant on water table conditions. Furthermore, visual observations showed that during times of low flow the Hororata River becomes dry soon after Mitchells Road but may flow again at the Selwyn confluence. The source for the flow at the Selwyn confluence appears to be from creeks draining springs L36/2031 and L36/0711. This phenomenon occurred months after any significant flow in the Selwyn River at Bealey Road and after springs near

A.

B.

C.

Figure 3.10 (A) Ephemeral spring-fed stream near Haldon Road (B) Discharge of a spring-fed creek into the Hororata River near Haldon Road (C) Permanent flowing spring-fed stream between Cotons Road and Derretts Road.

Haldon Road had gone dry and implies that the Hororata River may also lose flow to groundwater north of its current position east of Mitchells Road.

Although the Hororata River flowed along its full length for a significant period during this study it generally runs dry after Mitchells Road, approximately 4 km downstream from where it gains water from permanent spring-fed creeks. Pictures illustrating variations in flow at different reaches of the Hororata River are shown in figure 3.11.

3.3.4 Previous gauging results and recharge estimates

Previous gaugings performed on the Selwyn and Hororata rivers during the 1980s by NCCB (1983) and again in 1993 by Anderson (1994) showed similar results to this study. Anderson (1994) divided Selwyn River flows into low flow (< $1m^3/s$ at Whitecliffs) and moderate-high flow ($2m^3/s$ to $4m^3/s$ at Whitecliffs) events. It was estimated that $0.5m^3/s$ was lost to groundwater between Whitecliffs and Bealey Road during low flow events and $4m^3/s$ was lost to groundwater over the length of the Selwyn during moderate-high flow events (Anderson, 1994).

Additionally, Cooper (1980) estimated that the combined loses to groundwater from the Hororata, Hawkins and Waianiwaniwa rivers was approximately $2m^3/s$.

The nature of the Hororata River downstream from Derretts Road, where it both gains and loses flow, makes it difficult to estimate the recharge component to groundwater. However, assuming that most losses from the Selwyn River occur south of the current position of that river (as evidenced by piezometric contours and water chemistry) one could assume that the difference between losses from the Selwyn River between Coalgate and Gillanders Road and gains in the Hororota River downstream from Derretts Road (Table 3.4) are either retained in the Selwyn River as underflow or lost to groundwater between the Selwyn and Hororata rivers or south of the Hororata River. The input from rainfall recharge between the two rivers would also need to be factored into the calculations.

3.3.5 Waianiwaniwa and Hawkins Rivers

Both the Waianiwaniwa and Hawkins rivers generally lose all their flow to groundwater shortly after they emerge onto the Selwyn plains. For the duration of this study the Waianiwaniwa River typically became dry shortly before or a few hundred metres downstream from Homebush Road whilst the Hawkins River became dry soon after Auchenflower Road. Typical flows within the

Figure 3.11.Flow along the Hororata River (A) Typical flow at Sleemans Road, H1 (B) Flow at Milnes Road, H2 (C) Typical flow at Derretts Road, H4 (D) Ponding at Derretts Road (E) Flow at Haldon Road, H5, after addition of permanent springs (F) High flow at Gillanders Road (G) Gillanders Road when dry (H) Flow at Selwyn confluence, H6 (I) Selwyn confluence when dry.

Figure 3.12 Typical flows within the Hawkins River at Auchenflower Road (top) and the Waianiwaniwa River at Homebush Road (below).

Waianiwaniwa River at Homebush Road and the Hawkins River at Auchenflower Road are shown in figure 3.12.

Interestingly, losses from both these rivers during normal flows coincide with the intersection of these rivers with the Hororata fault. This suggests that the Hororata fault may be acting as a preferred flow path for groundwater movement near these two rivers but further investigations are required.

During the middle of August both the Waianiwaniwa and Hawkins rivers became flooded and flowed over their full length into the Selwyn River. Flood flows were sustained near the Selwyn River for only a few days. Flow within the Waianiwaniwa River at Coaltrack Road, several hundred metres before the Selwyn River, is shown in figure 3.13. Following flooding, flows within the Waianiwaniwa River were maintained further downstream for a significantly longer period than the Hawkins River. This may simply reflect different catchment zones between the rivers but could also imply that the Hawkins River loses the majority of its flow close to the foothills during flooding. NCCB (1983) reported that flood flows of up to $3m^3/s$ are lost from the Hawkins river to groundwater upstream of Darfield.

Figure 3.13 Surface flow in the Waianiwaniwa River at Coaltrack Road shortly before the confluence with the Selwyn River on the 19th August 2004.

Water levels in well L36/0043, located a few hundred metres from the Waianiwaniwa River near Coaltrack Road (figure 3.5), increased dramatically following flooding within the river (section 4.6.1.1). This suggests that the Waianiwaniwa and Hawkins rivers have a significant effect on adjacent shallow groundwater levels during flooding events.

3.4 Summary

3.4.1 Springs

The majority of springs within the field area are depression springs and outcrop within two distinct belts. One belt is located several hundred metres north of the Hororata River between Cotons Road and Derretts Road, the other belt is located east of Haldon Road.

Spring flow between Cotons Road and Derretts Road is permanent and likely to be sourced from surface losses from the Selwyn River shortly after Coalgate. Flow within all other springs is intermittent and strongly dependant on surface flows within nearby reaches of the Selwyn River.

3.4.2 Selwyn River

Gaugings along the Selwyn River show that significant surface losses occur within the upper reaches of the river between Coalgate and Bealey Road and further downstream between Greendale and Dunsandel. Water levels in shallow wells indicate that the river provides significant recharge to the shallow aquifer. Surface losses are strongly dependant on water table conditions but also depend on total flow and duration of flow peaks.

3.4.3 Hororata River

Gaugings along the Hororata River show that significant gains in surface flow occur between Derretts Road and the Selwyn confluence. The source for this increased flow is from numerous spring-fed creeks derived from surface losses from the Selwyn River. Water levels in shallow wells and visual observations of river flow suggest that the Hororata River significantly recharges the shallow aquifer south of the present course of the river.

3.4.3 Waianiwaniwa and Hawkins rivers

Both the Waianiwaniwa and Hawkins rivers generally lose all their surface flow to groundwater shortly after they emerge onto the Selwyn plains. Losses coincide with the intersection of the rivers with the Hororata Fault which indicates that the Hororata Fault has a significant influence on the groundwater system within the upper plains area. Water levels show that both rivers have a significant effect on adjacent shallow groundwater levels during flooding events within the rivers.

Chapter Four

Hydrogeology

4.1 Introduction

The groundwater resources of the upper Selwyn plains are extremely important. In most areas, groundwater provides the sole source of water for irrigation and public water supplies. To prevent over-abstraction of the groundwater resource a thorough understanding of the aquifers in which the groundwater resides and the different recharge sources are required.

This chapter describes and evaluates the groundwater resources of the upper Selwyn plains. The various aquifers are identified are described in terms of their spatial and vertical distribution and groundwater flow direction determined by a piezometric survey. Water levels were measured in a number of wells penetrating the different aquifers to assess the likely recharge sources.

4.2 Aquifer identification

4.2.1 Problems with identifying aquifers

Aquifers are very difficult to identify from borelog descriptions within the mid and upper plains for a variety of reasons:

- The contrasts between gravel deposits are not easily discernable from borelog descriptions and it is likely that there are only subtle lithological differences between aquifer and aquitard sediments. In contrast, coastal deposits are easily discernable in borelog descriptions because of the distinct coarse (aquifer) and fine (aquitard) sequences present towards the coast

- Almost all borelog descriptions have been recorded by drillers who are untrained in geological logging and there has been no industry standard for describing gravels, therefore the same sediments are often described in different ways

- It is very difficult to describe sediments accurately from modern rotary drilling techniques because clasts are often broken and fine material is washed out during the drilling process. The majority of wells have been drilled by this technique

- Aquifers are likely to flow through numerous permeable old remnant channels and there is likely to be local variation in permeability, grain-size and sorting. This variation is likely to be reflected in borelog descriptions

The most common method to identify aquifers within the upper plains areas is to supplement borelog descriptions with well screen and/or specific capacity information. However, well screens are assumed to penetrate the width of the aquifer, which is seldom the case, and specific capacity data can be unreliable.

4.2.2 Groundwater cross-sections

Aquifers were identified by screen distributions, water levels and borelog descriptions through hydrogeological cross-sections (figures 4.1 and 4.2). Figure 4.1 was constructed approximately parallel to groundwater flow and figure 4.2 approximately perpendicular to groundwater flow. The location of cross-sections lines, are shown in figure 4.3. Borelogs and screens for wells within 500 metres of the section lines were projected onto the cross-sections and their height vertically adjusted to intercept with ground level. Borelog descriptions were divided into 3 gravel types to aid in the identification of aquifers (1) free gravels or water-bearing gravels, which most likely represent aquifer lithologies (2) gravel and sand lithologies, which may indicate more permeable water-bearing layers and (3) claybound gravels, which most likely represent non-aquifer lithologies. Highest and lowest recorded water levels for wells within aquifers 1 and 2 were also plotted on the cross-sections. Water level data for wells was variable, some wells had several years of data and others only a handful of readings.

Figure 4.1 shows that three aquifers can be identified within the field area. Aquifer 1 occurs between approximately 0 and 30 metres, aquifer 2 between approximately 40 and 85 metres and aquifer 3 from approximately 100 metres below the surface. The thickness of and water level variations in aquifer 3 could not be determined because of the lack of deep wells within the field area. The lowest water level line for aquifer 2 approaches the lower extent of the aquifer further inland. This would suggest that wells penetrating aquifer 2 would have less available drawdown (and thus have a greater possibility of being less reliable) with progressive distance inland.

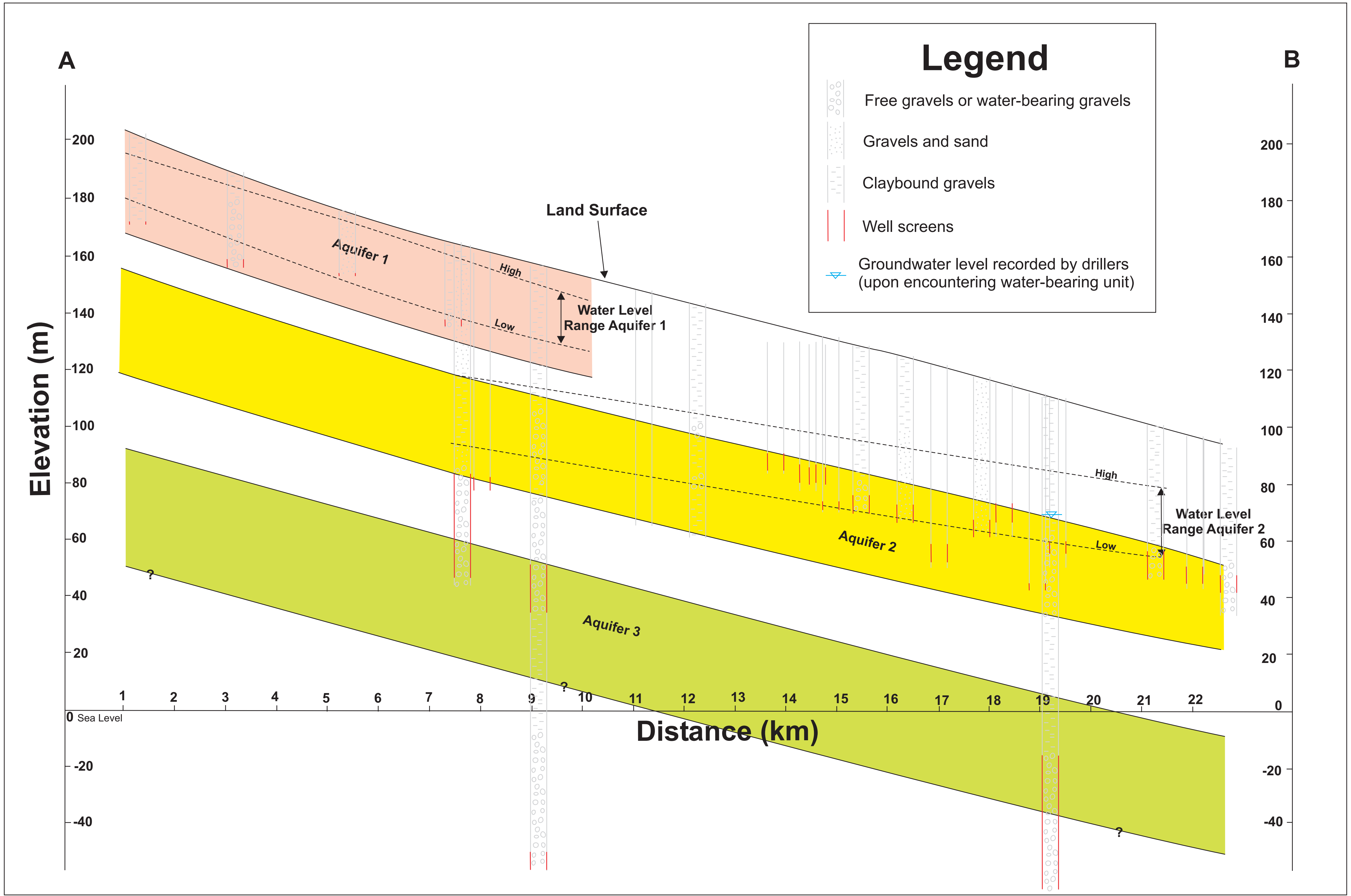


Figure 4.1 Cross-section A - B approximately parallel to groundwater flow.

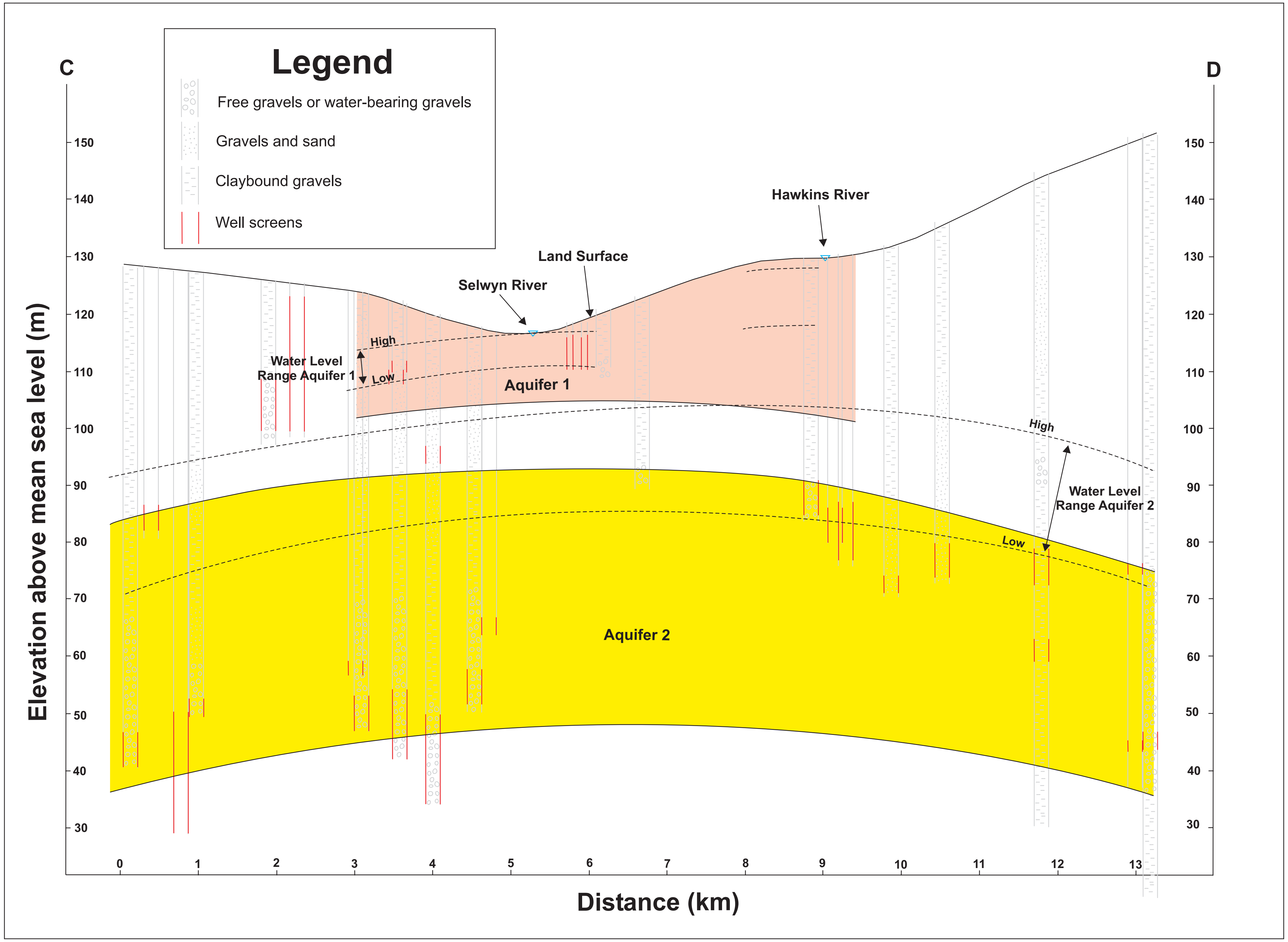


Figure 4.2 Cross-section C-D approximately perpendicular to groundwater flow.

Furthermore, water levels suggest that wells inadequately penetrating aquifers 1 or 2 may run dry during periods of low water levels.

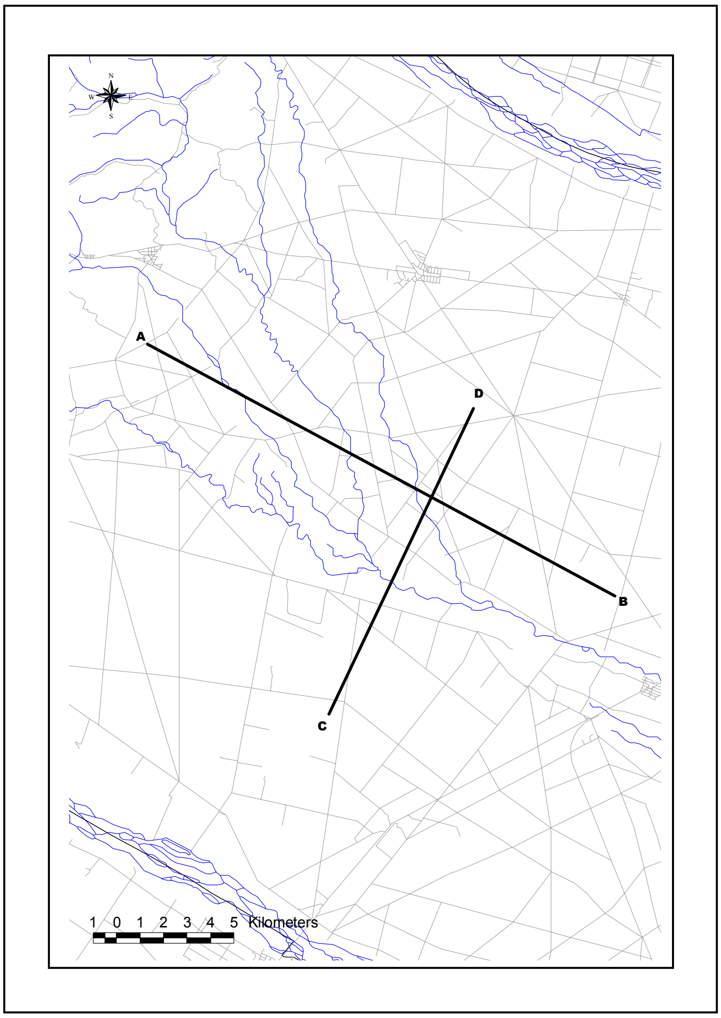


Figure 4.3 Map showing location of cross-sections.

Figure 4.2 shows that water levels in both aquifers 1 and 2 are highest below the Selwyn River, and steadily drop with distance from the river. This indicates that both aquifers 1 and 2 receive significant recharge from the Selwyn River and/or its tributaries. Water level elevations in aquifer 1 near the Hawkins River are significantly higher than those underneath the Selwyn River. This suggests that the shallow aquifer within the Greendale area receives little or no recharge from the Selwyn River and that aquifer 1 may not be continuous between the Selwyn River and Greendale. Water levels, like figure 4.1, indicate that wells inadequately penetrating aquifers 1 and 2 may run dry during periods of low water levels.

The shallow aquifer is not overlain by fine sediment and can be considered an unconfined aquifer. Storativity data (Appendix 4.1) for wells penetrating aquifers 2 and 3 indicate that aquifer 2 is semi-confined and aquifer 3 is semi-confined to confined. Aquifers 1 and 2 exist within areas surrounding the Selwyn River and its tributaries, which suggest that these aquifers receive significant recharge from the Selwyn River.

Borelogs indicate that aquitard material is dominantly composed of sandy gravels or claybound gravels of variable permeability. This indicates that significant leakage can occur between the different aquifers. No attempt was made to identify boundaries between different gravel formations at depth because of the difficulties in distinguishing boundaries through borelog descriptions. It is likely that the shallow aquifer occurs dominantly within Springston and Burnham Formations derived from the Selwyn River and/or its tributaries. Deeper aquifers occur within Burnham, Windwhistle, Woodlands and Hororata Formation gravels at depth.

A plot of specific capacity versus depth for wells within the field area was also produced (figure 4.4). This plot shows similar aquifer groupings to those of the stratigraphic cross-sections, which gave confidence to the results of the latter.

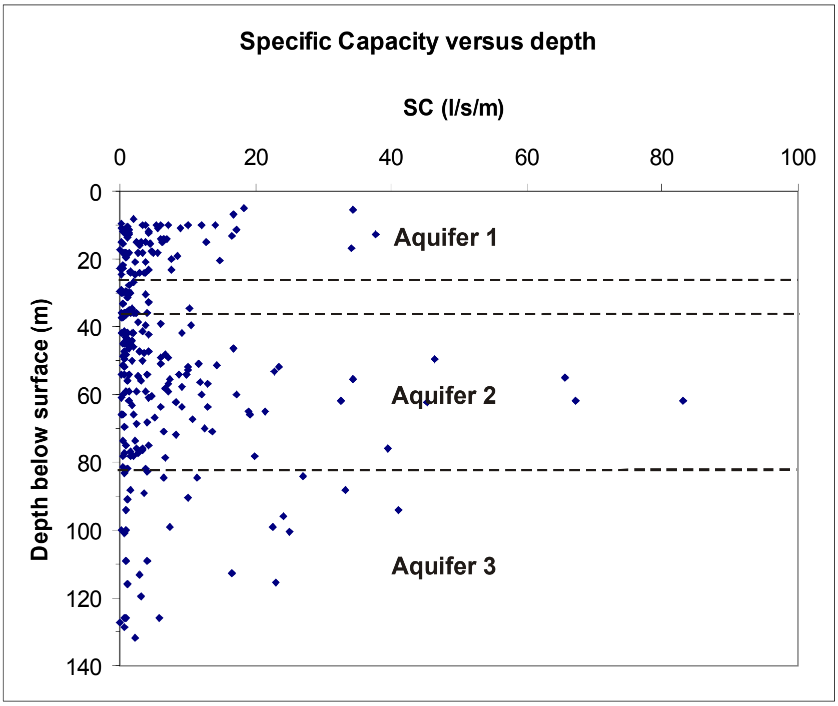


Figure 4.4 Specific capacity versus depth for wells within the field area.

4.3 Specific Capacity

Specific capacity is a measure of the productivity of a well and is obtained by dividing the rate of discharge of water from the well by the drawdown of the water level in the well and is typically expressed as litres/second/metre. The specific capacity of an individual well is determined by the aquifer characteristics, number of hours the well has been pumped prior to measuring drawdown, and well construction and will generally decrease with time as the drawdown increases. Overall, a higher specific capacity indicates a more transmissive aquifer.

A plot of specific capacities within the different aquifers[1] is shown in figures 4.5 – 4.7. Figure 4.5 shows that specific capacities in wells penetrating aquifer 1 are generally higher to the south of the present course of the Selwyn River between Dunsandel and Greendale. This could possible indicate influent seepage from the Selwyn River to the shallow aquifer south of the present course of the river. Sparse specific capacity data further inland make it difficult to observe any trends between Coalgate and Greendale.

Specific capacities for aquifer 2 (figure 4.6) are generally higher to the south of the Selwyn River and to the east of Greendale. Once again the higher values south of the Selwyn River between Dunsandel and Greendale may indicate influent seepage from the Selwyn River into aquifer 2.

Specific capacities for aquifer 3 (figure 4.7) show a different pattern to aquifers 1 and 2 and are generally higher in wells in close vicinity to the Selwyn and Hororata rivers and between the Hororata and Rakaia rivers. Specific capacity is generally lower between the Hawkins and Waimakariri rivers.

No apparent trends of increasing or decreasing specific capacity with depth could be observed. The plot of specific capacity versus depth (figure 4.4) also shows that there are no or little trends within specific capacity values with depth.

4.4 Transmissivity

Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient and is usually expressed as m^2/day. Transmissivities for wells within the field area, as obtained from aquifer pumping tests, are shown in figure 4.8. The quality of the

[1] For simplicity the depth range for different aquifers has been assigned as 0-30m (shallow aquifer), 30-80m (aquifer 2) and >80m (aquifer 3).

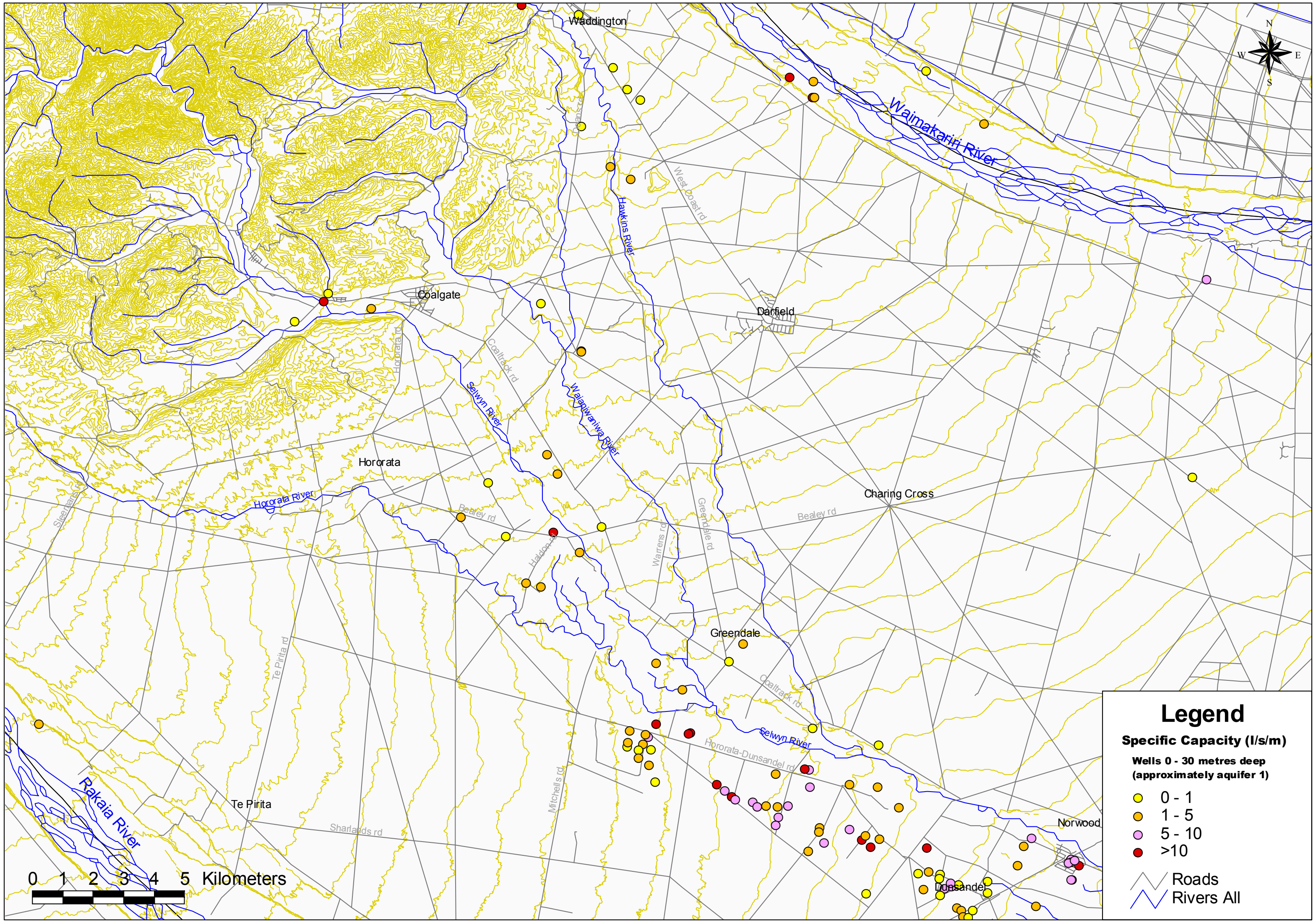


Figure 4.5 Specific capacity distribution for wells between 0-30 metres (approximately aquifer 1).

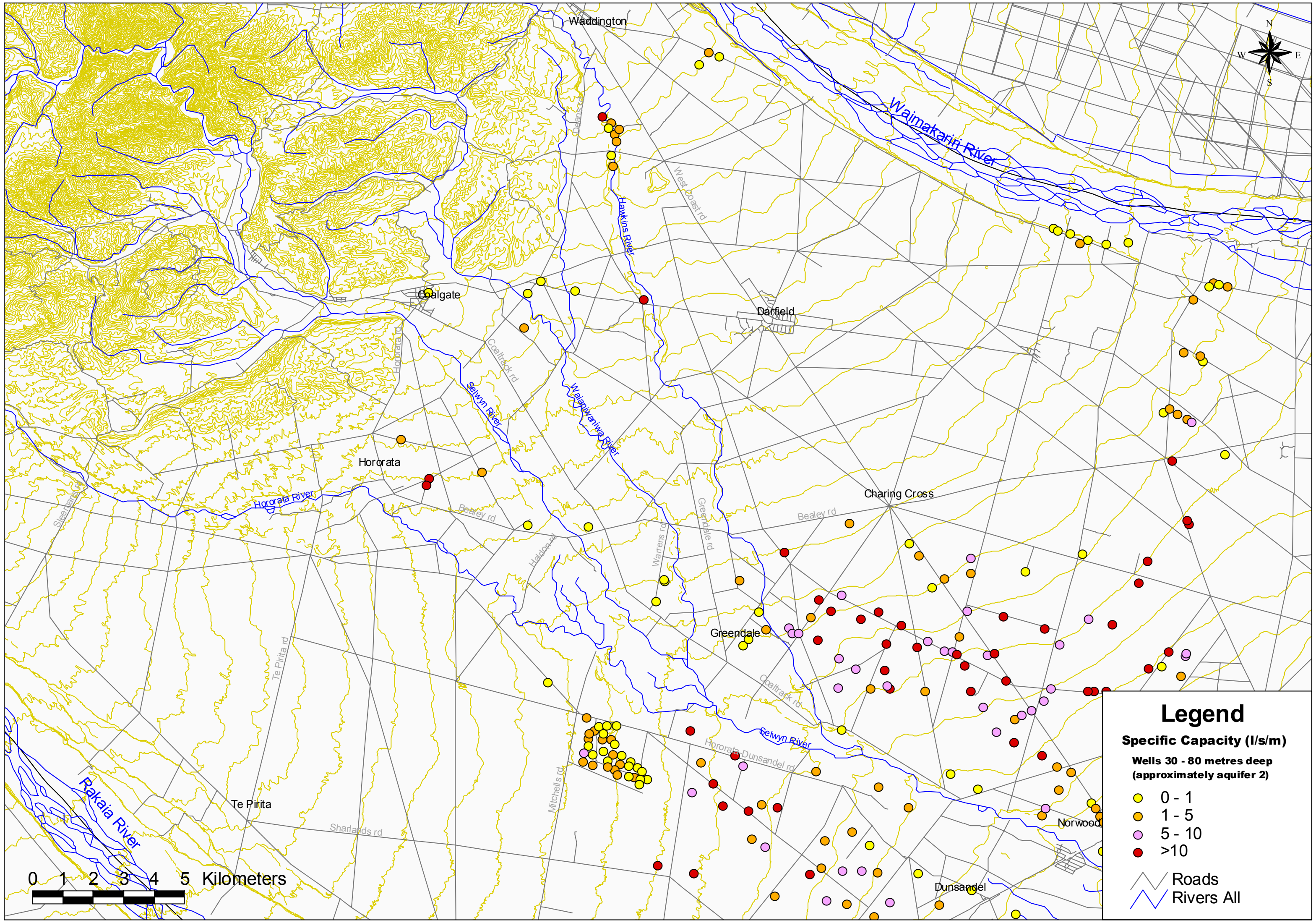


Figure 4.6 Specific capacity distribution for wells between 30-80 metres (approximately aquifer 2).

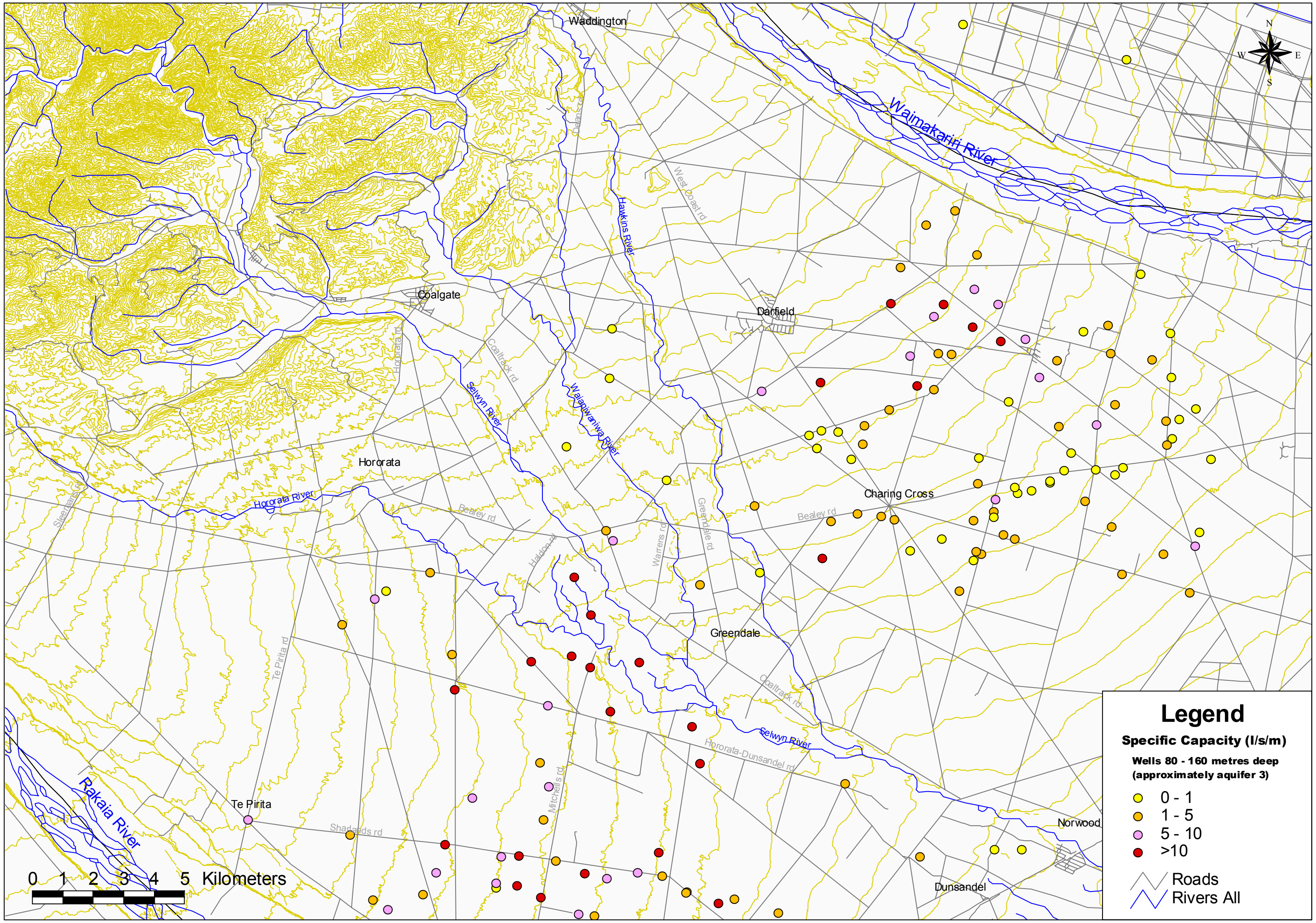


Figure 4.7 Specific capacity distribution for wells between 80-160 metres (approximately aquifer 3).

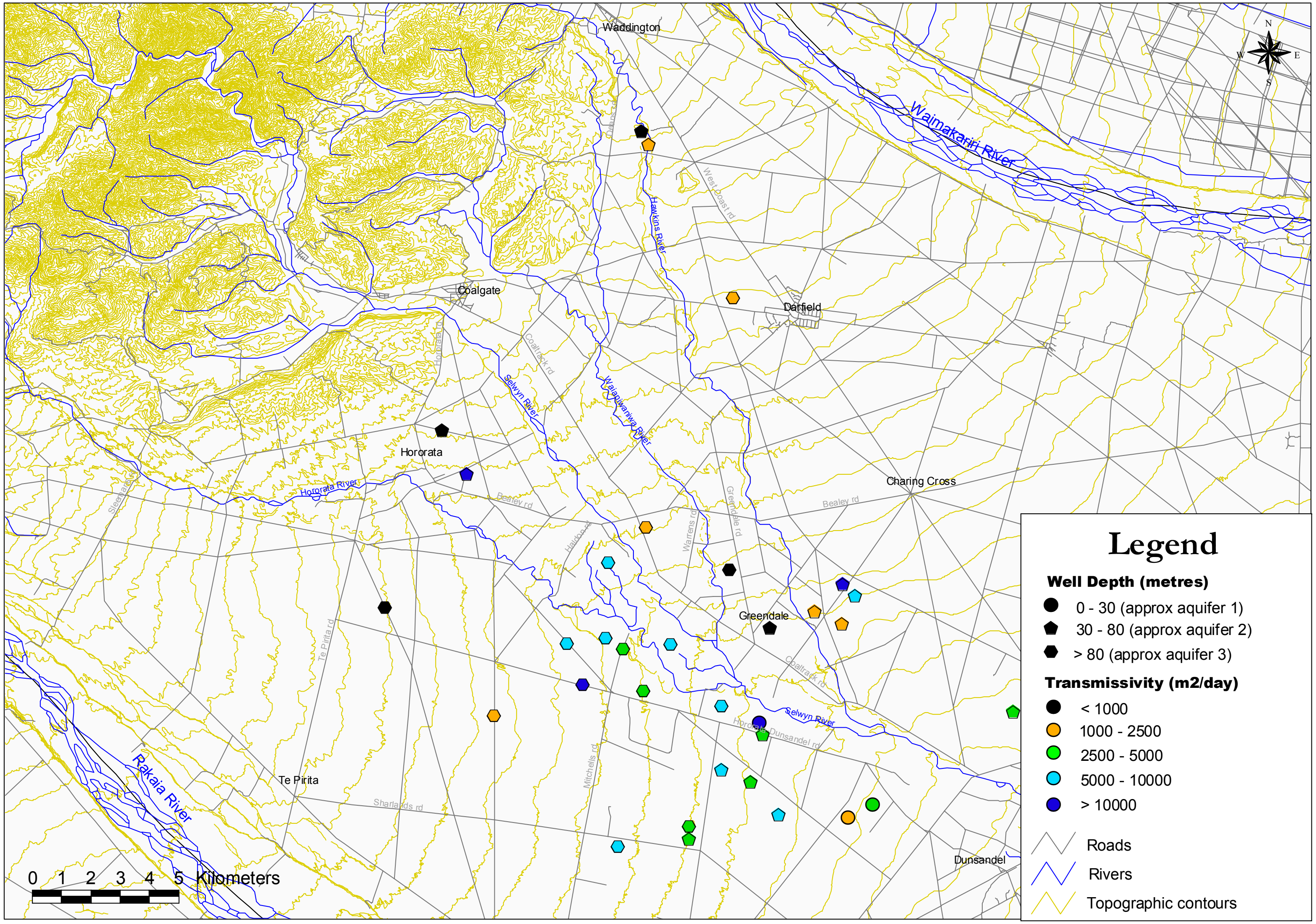


Figure 4.8 Transmissivities for aquifer test wells.

transmissivity data is variable, ranging from single wells pumped for only a few hours to wells pumped for several days with multiple observation bores.

In general, figure 4.8 shows that transmissivities are higher in wells penetrating aquifers 1, 2 and 3 to the south of the Selwyn and/or Hororata rivers. The higher transmissivities close to the Selwyn River suggest that influent seepage from the river is recharging to aquifers 2 and possibly 3 in this area which is also indicated by groundwater chemistry. Wilson (1973) suggested that influent seepage is likely to remain in the deposits of the river from which they formed. The higher transmissivities south of the Hororata and Selwyn rivers may suggest that old gravel deposits of the Selwyn River extend to depth south of the current location of the Selwyn River.

Results of pumping tests on wells within the field area are shown in Appendix 4.1.

4.5. Groundwater Flow

A piezometric survey was carried out in July 2004 for a total of 128 wells (66 wells in aquifer1, 38 wells in aquifer 2 and 24 wells in aquifer 3) located throughout the upper Selwyn plains. Figures 4.9 – 4.11 show the piezometric contours, i.e. lines connecting points of equal height of static water level surface above mean sea level, for aquifers 1, 2 and 3 respectively. Arrows drawn at right angles to the piezometric contours indicate the direction of groundwater flow. The survey was undertaken during a time when water levels were recovering from a dry irrigation season and before the full onset of a wet winter season. Therefore groundwater levels during the piezometric survey can be considered to represent aquifers during a reasonably stressful state. Groundwater well elevations were later surveyed in to an accuracy of less than 0.5m by DGPS. Results of the piezometric survey for the different aquifers are explained below. Details and water levels for wells used for the piezometric survey are shown in Appendix 4.2.

4.5.1 Aquifer 1

Piezometric contours for aquifer 1 (figure 4.9) show that shallow groundwater travels in a general southeasterly direction from the foothills with a consistent hydraulic gradient of approximately 6m/km. Contours near the Selwyn River in its upper reaches near the foothills are concave in the downstream direction and indicate significant surface losses from the Selwyn River to the shallow aquifer between the Selwyn and Hororata rivers. Similarly, contours along

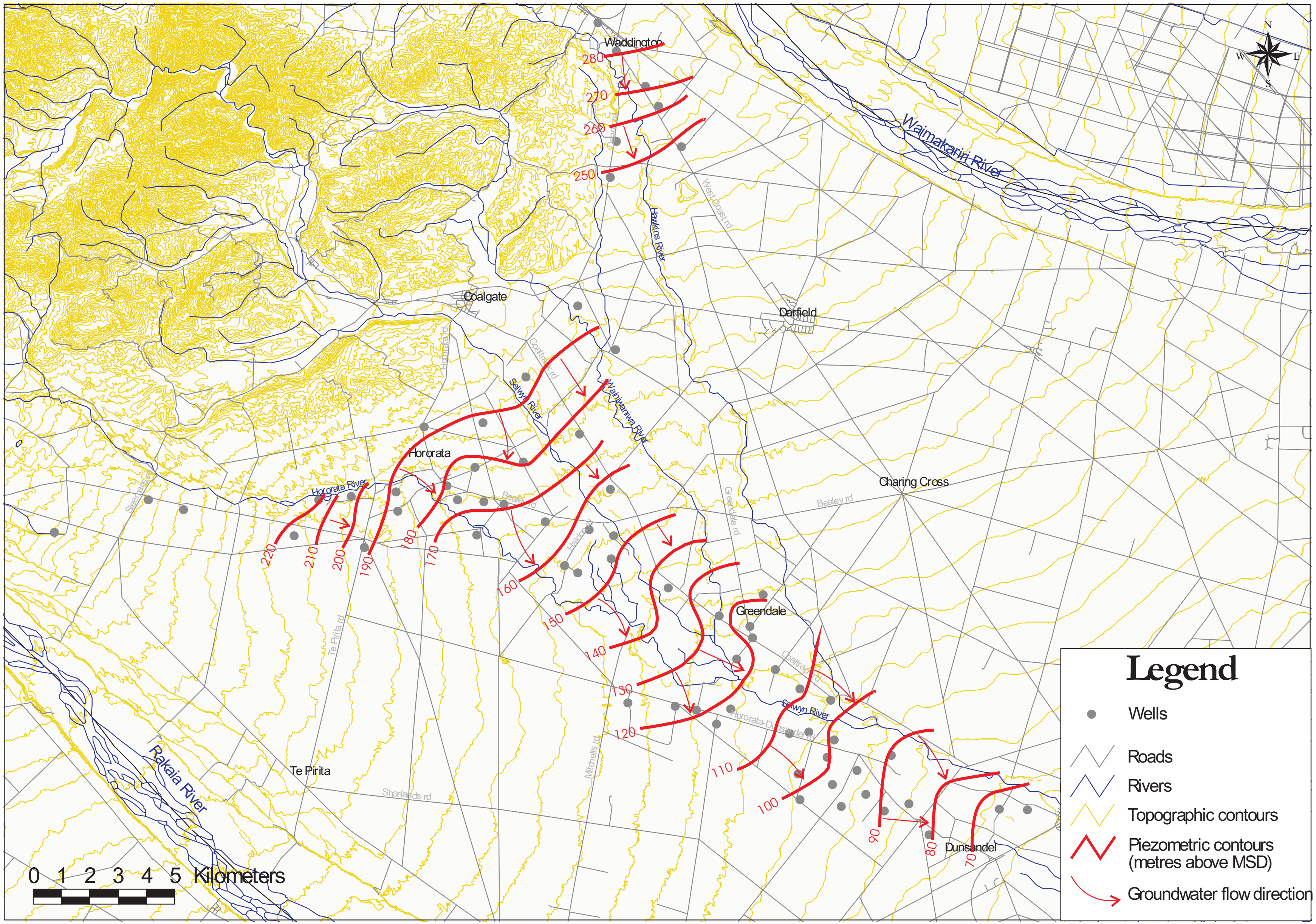


Figure 4.9 Piezometric contours for aquifer 1.

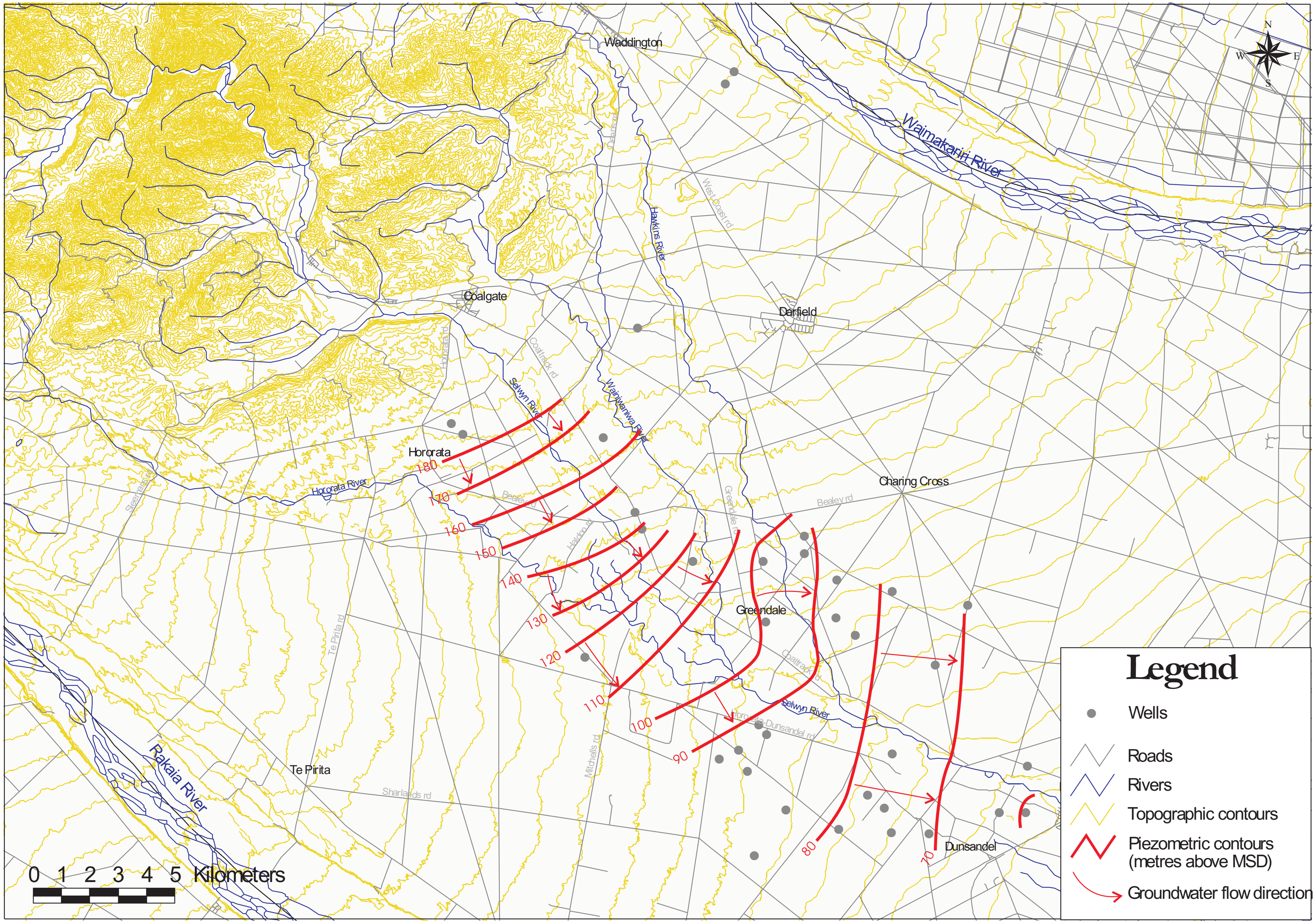


Figure 4.10 Piezometric contours for aquifer 2.

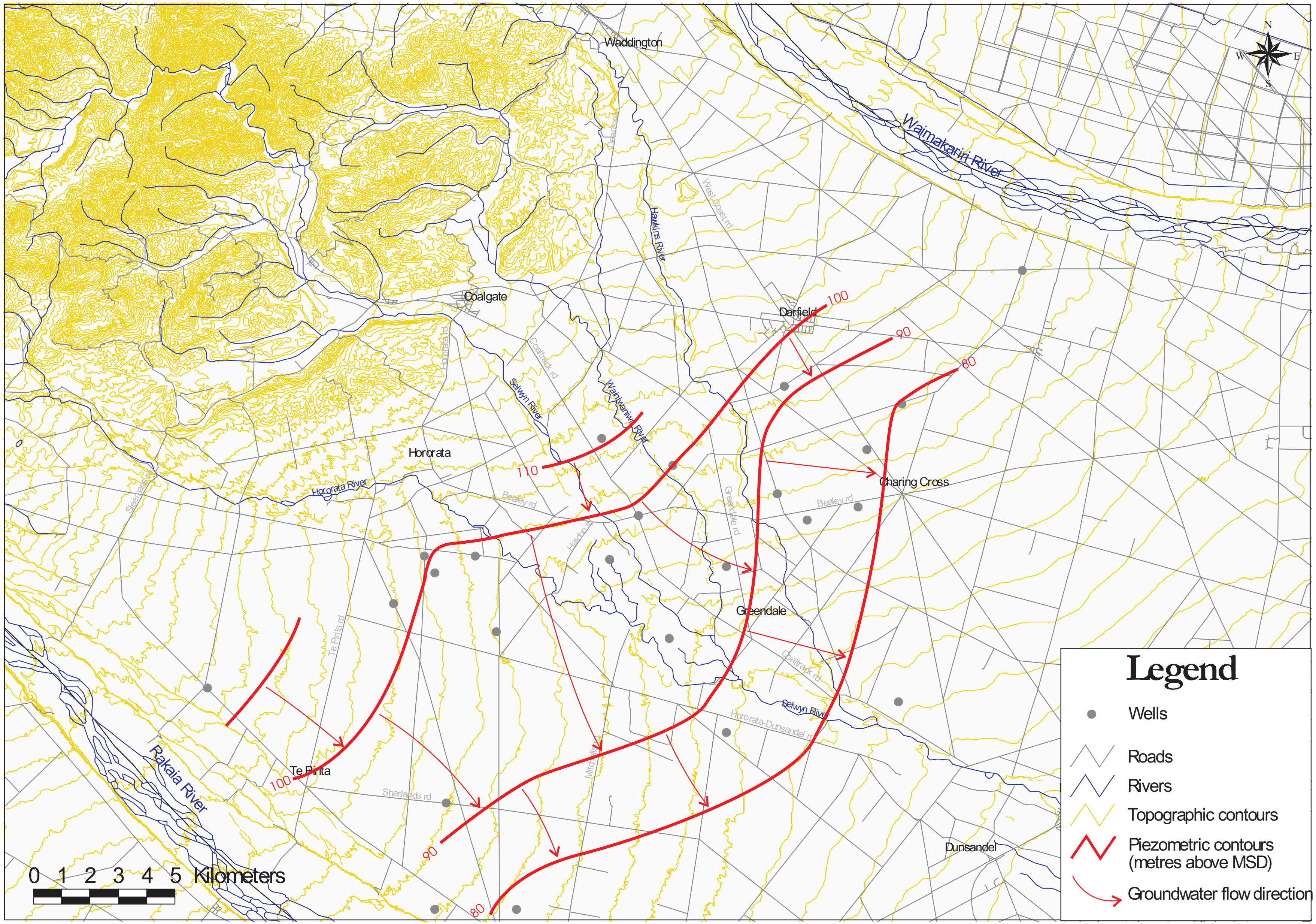


Figure 4.11 Piezometric contours for aquifer 3.

the lower reaches of the Hororata River indicate significant losses from the Hororata River to the shallow aquifer south of the Hororata River.

Contours occur in close vicinity to the Selwyn River and its tributaries, which suggests that the shallow groundwater system is strongly dependant on losses from those rivers.

Contours near the Waianiwaniwa River at Greendale are strongly convex upstream and may indicate some possible geological control on the shallow groundwater system in this area.

4.5.2 Aquifer 2

Piezometric contours for aquifer 2 (figure 4.10), show that groundwater travels in a general southeasterly direction. The flow pattern is less complicated from that of the shallow aquifer. However, there is a strong hydraulic gradient change from approximately 7m/km in the upper region to approximately 3m/km in the lower regions. Curvature near the Selwyn River below Greendale, indicate that aquifer 2 (south of the present course of the Selwyn River) receives recharge from the Selwyn River. This recharge is probably via leakage from aquifer 1.

Contours occur within close proximity to the Selwyn River and its tributaries, and this suggests these rivers have a strong influence on groundwater flow within aquifer 2.

4.5.3 Aquifer 3

Piezometric contours for aquifer 3 (figure 4.11), like aquifers 1 and 2, show that groundwater flows in a general southeasterly direction. Well coverage for aquifer 3 was low and contours were drawn assuming connectivity of aquifer 3 across the plains between the Waimakariri and Rakaia rivers. Contours suggest that aquifer 3 receives significant recharge to the south of the Selwyn fan. This is likely to be through the slow leakage of Selwyn River derived groundwater through aquifers 1 and 2.

4.6 Groundwater level fluctuations

The origin of all groundwater beneath the Canterbury Plains is from rainfall. Rainfall can enter the groundwater system through direct infiltration at the surface, runoff and infiltration of rainfall falling on the foothills and seepage of river water derived from high catchment precipitation. The presence of deeper aquifers in close vicinity to the foothills suggests that lateral seepage through fractures within older relatively impermeable Tertiary foothills sediments at depth may also be significant. Additionally, leakage from stock water races and irrigation water may recharge the shallow aquifer.

Outputs from the aquifer system include groundwater abstractions and throughflow into the lower plains region.

Water levels in wells fluctuate in response to variations within the different recharge sources.

4.6.1 Seasonal fluctuations

Water levels in approximately 40 wells within the field area were measured manually every 2 weeks from June 2004 to June 2005 in order to evaluate seasonal fluctuations and possible recharge sources. In addition, divers (automatic groundwater recording devices) were installed in 5 wells with water levels recorded every 1 hour. Monitoring wells were chosen based on accessibility, location and usage. Selected wells measured throughout the duration of this study, and used in the following section, are shown in figure 4.12.

4.6.1.1 Aquifer 1

Hydrographs for selected wells within aquifer 1 are shown in figure 4.13. In general, water levels in shallow wells within close proximity to the Selwyn River and penetrating Springston Formation gravels, show immediate and strong fluctuations in response to flow within nearby reaches of the river (e.g. L36/0205 and L36/1193). This indicates that losses from the Selwyn River provide significant recharge to the shallow aquifer. Water levels in L36/1193 rapidly rise when the Selwyn River flows at Bealey Road.

Water levels within wells in the upper plains between the Selwyn and Hororata rivers (e.g. L35/0604) show a delayed response to Selwyn River flow at Whitecliffs. The magnitude of these fluctuations, are lower than those of wells immediately adjacent to the river which indicates a more constant source for groundwater recharge. Water chemistry and river gaugings suggest the major source for groundwater in this area is surface losses from the Selwyn River shortly after it emerges onto the plains after Coalgate.

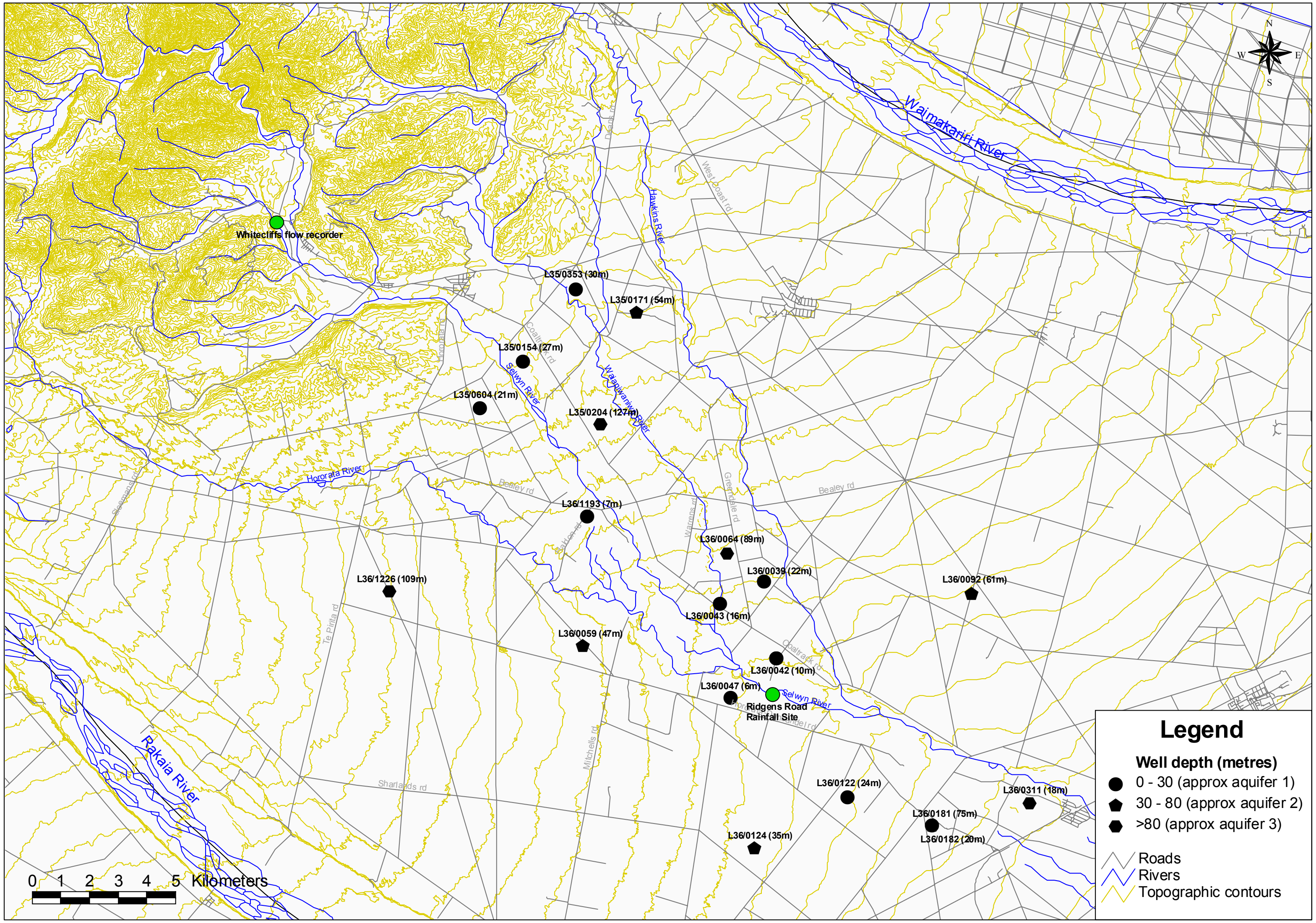


Figure 4.12 Selected wells with water levels measured during this study and used in section 4.6.

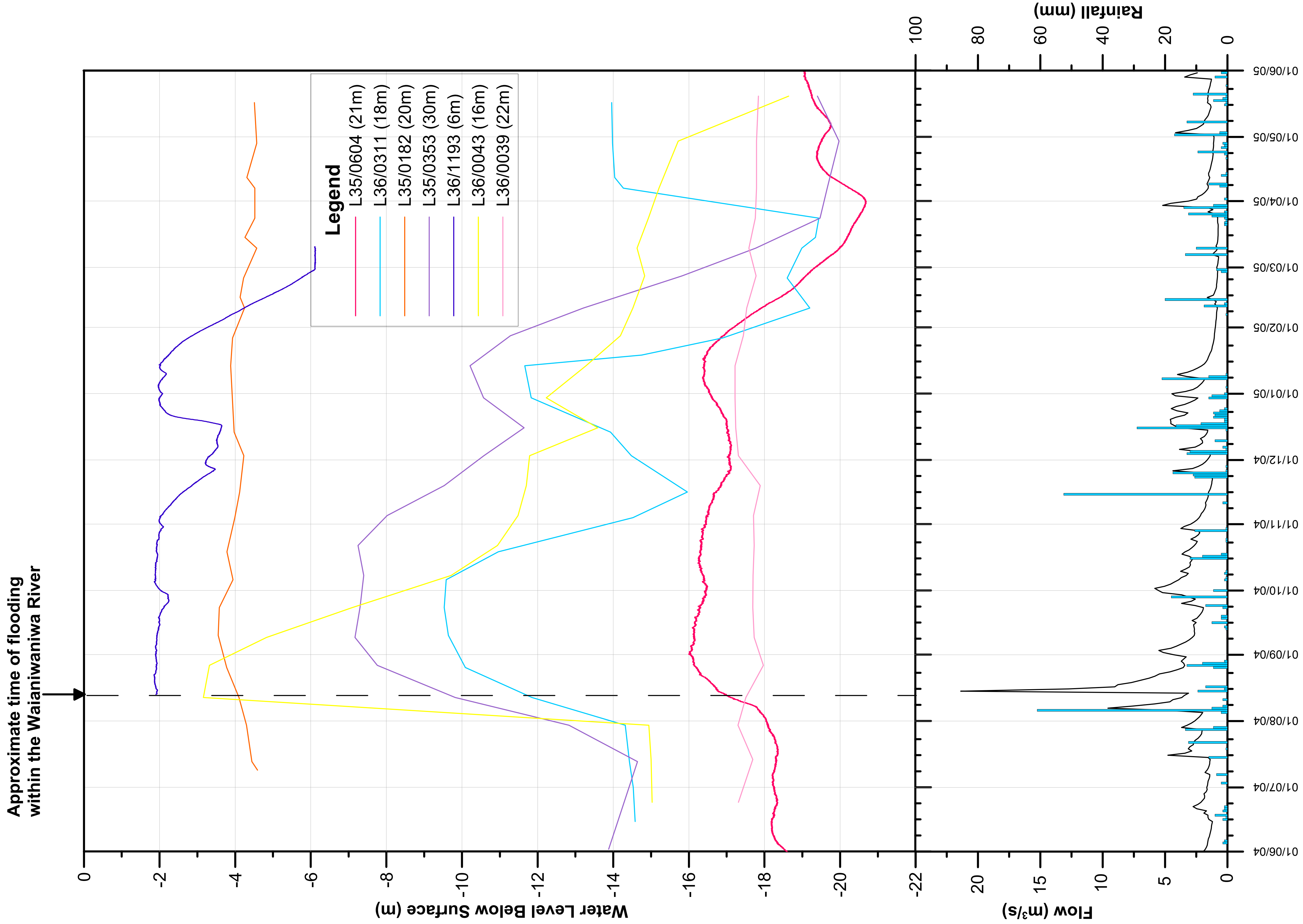


Figure 4.13 Hydrogrpahs of selected shallow levels, flow within the Selwyn River at Whitecliffs and rainfall at Ridgens Road.

In general, fluctuations in shallow water levels decline with distance from the Selwyn River. The hydrograph for well L36/0182, located near Dunsandel, shows little response to flow within the Selwyn River and is likely to be recharged dominantly from rainfall.

Wells L35/0353 and L36/0043, located within close proximity to the Wainaniwaniwa River near the foothills and near the confluence with the Selwyn River, respectively, increased significantly during flooding events in the Wainaniwaniwa River. This suggests that the Waianiwaniwa River significantly affects the shallow aquifer during flood events. Interestingly, well L36/0039 located between the Waianiwaniwa and Hawkins rivers, showed no response to flood flows within those rivers. This implies that surface losses in the lower reaches of these rivers, during flood events, may only recharge the shallow aquifer within Springston Formation gravels immediately surrounding the rivers.

NCCB (1983) identified a high correlation between daily flow in the Selwyn River at Whitecliffs and rainfall measured at Hororata. This makes it difficult to distinguish the effects of rainfall infiltration from river recharge in wells not located immediately adjacent to the Selwyn River.

4.6.1.2 Aquifer 2

Hydrographs for selected wells penetrating aquifer 2 are shown in figure 4.14. Water levels within wells between the Waianiwaniwa and Hawkins rivers in the upper plains (e.g. L35/0171) show a strong response to flooding within those rivers. This implies that there is significant and rapid downwards leakage of groundwater from aquifer 1 in that area.

Water levels in aquifer 2 south of the Hororata River (e.g. L36/0059) show little variation. This could suggest a constant recharge source or slow seepage through less permeable gravels within that area.

Water levels in L36/0092 and L36/0064 indicate that rainfall recharge dominates aquifer 2 within the Greendale area.

4.6.1.3 Aquifer 3

Water levels in wells penetrated aquifer 3 are generally highest during the winter and spring months of July through to November. These trends probably represent a delayed response to winter rainfall.

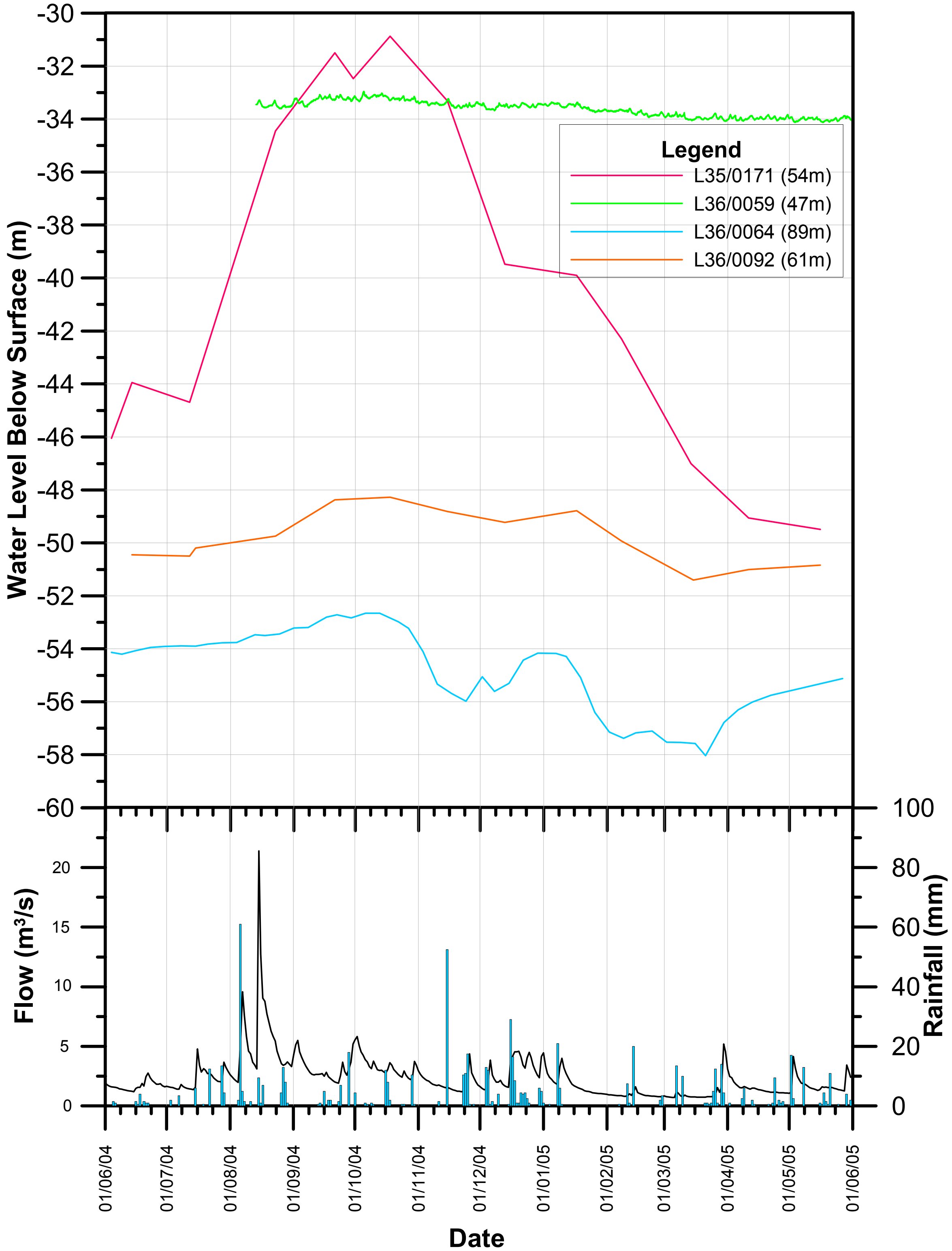


Figure 4.14 Hydrographs for selected wells within aquifer 2, flow within the Selwyn River at Whitecliffs and rainfall at Ridgens Road.

4.6.2 Short-term fluctuations

Short-term fluctuations within wells in the upper Selwyn plains are caused by atmospheric pressure, rainfall infiltration and pumping effects. Loading of the unsaturated zone when soil moisture levels are high may also cause water level fluctuation within underlying aquifers.

Well pumping results in a lowering of the piezometric surface in all directions from the well, which is called a cone of depression. The size of the cone of depression depends on the hydraulic properties of the aquifer and the rate and duration of pumping. An example of the interference effects of nearby pumping on adjacent shallow groundwater levels is shown in well L36/0122 (figure 4.15). The combined effects of a number of wells pumping together may significantly lower groundwater levels during the irrigation season.

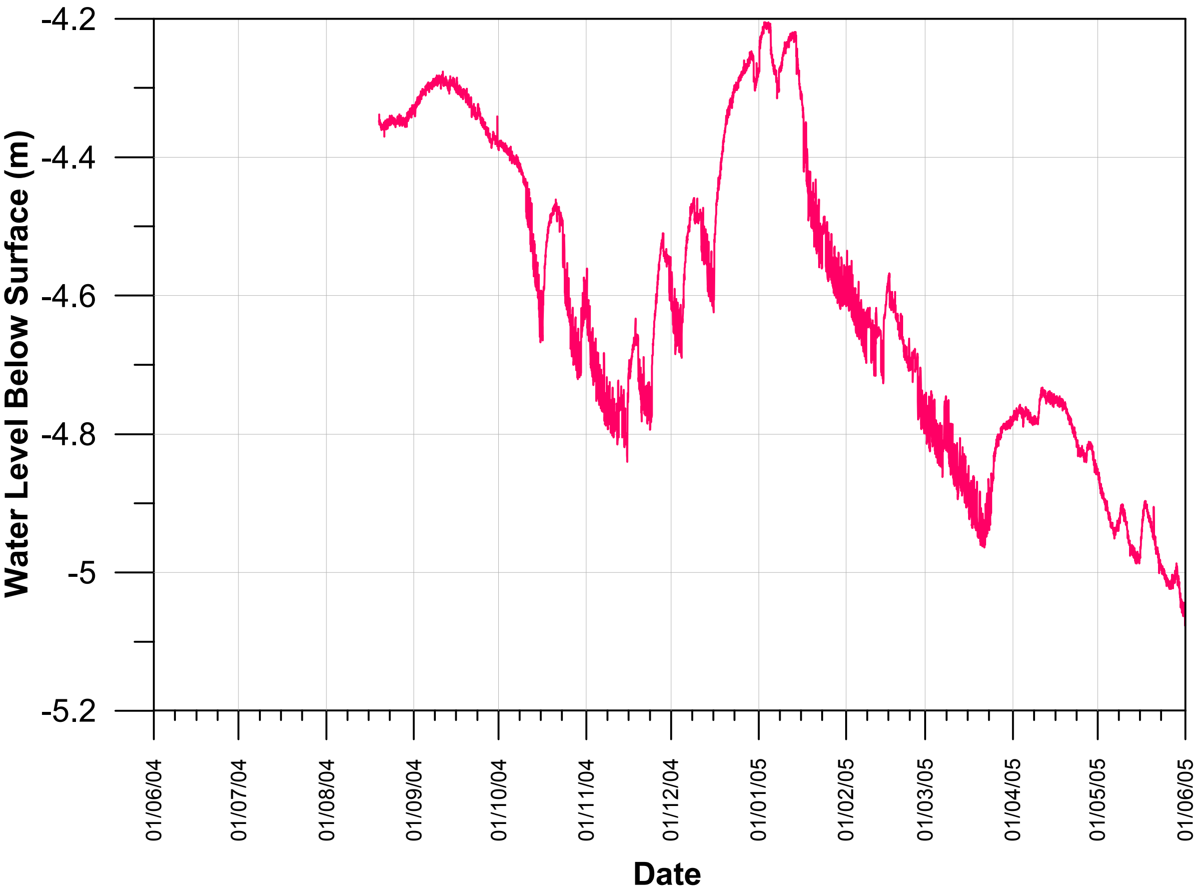


Figure 4.15 Hydrograph for well L36/0122 (24m), showing typical interference pattern (sharp fluctuations in water levels).

4.6.3 Long-term trends

Long-term fluctuations in groundwater levels provide a direct measure of the changes in aquifer storage with time.

Wells within the upper Selwyn plains are currently displaying a declining trend in groundwater levels with many wells reaching record low levels. This is illustrated in figure 4.16, which shows hydrographs for wells L36/0181, L35/0204 and L36/0124. All three wells have water level records dating back to the late 1970's. The pattern for L36/0181 shows that this well is significantly affected by groundwater pumping (interference) from approximately 1997 onwards.

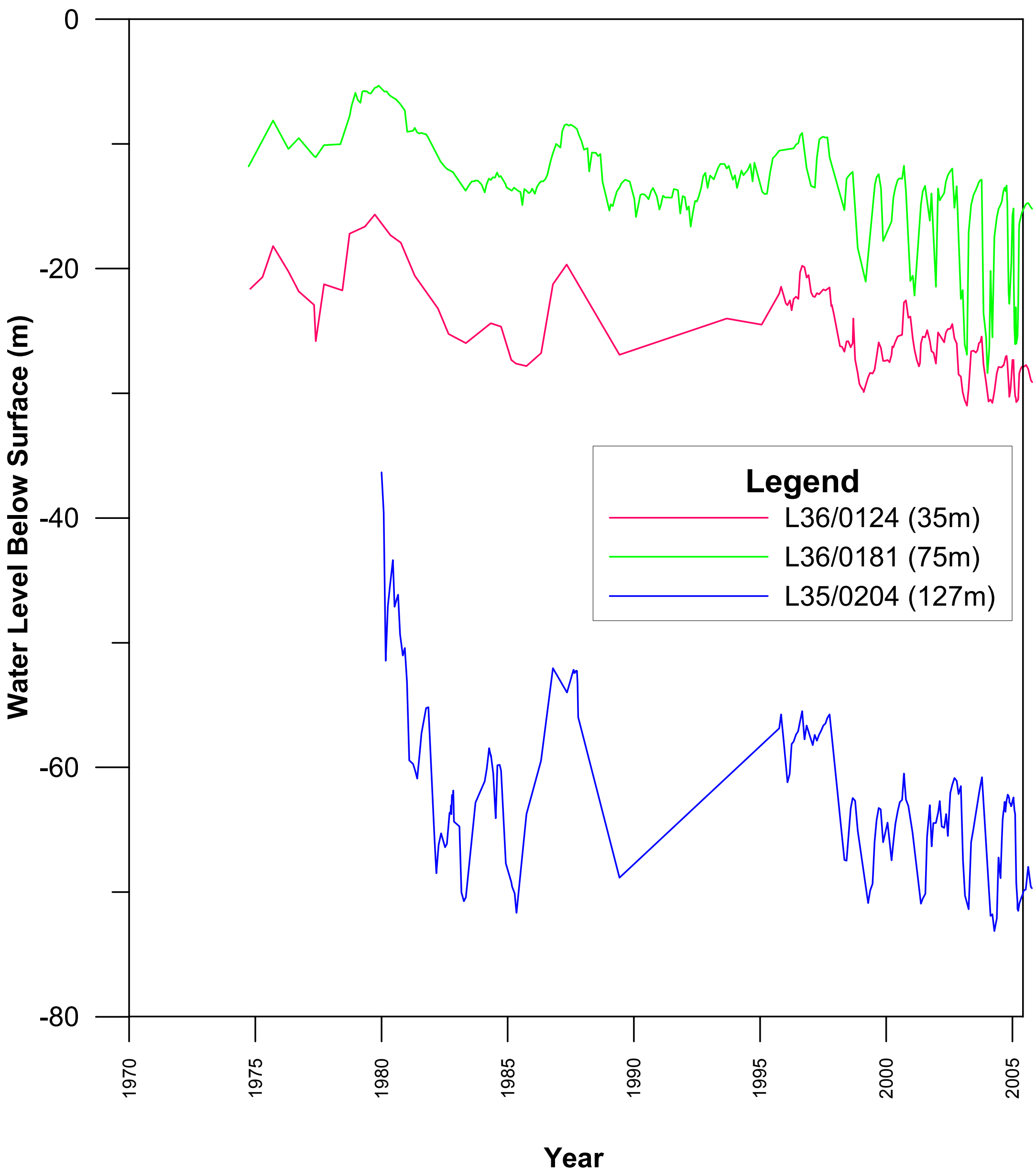


Figure 4.16 Hydrographs for wells L35/0204, L36/0124 and L36/0181 showing long-term declining trends in groundwater since the 1970s.

Long-term declining groundwater levels may be caused by a long-term decrease in rainfall recharge to the aquifers or an increase in groundwater abstractions.

4.7 Summary

Cross-sections constructed from borelog descriptions, screen distributions and water levels show that at least three aquifers occur within the gravel deposits of the upper Selwyn plains. Aquifer 1 occurs between approximately 0 – 30m, aquifer 2 between 40-85m and aquifer 3 greater than 100m below the surface. The thickness of aquifer 3 could not be determined because of the lack of deep wells within the area. Aquifers 1 and 2 occur within close proximity to the Selwyn River and its tributaries.

Borelog descriptions and storativity data show that aquifer 1 is unconfined, aquifer 2 semi-confined and aquifer semi-confined to confined. Significant leakage of groundwater occurs between the different aquifers.

Specific capacity and transmissivity data show no apparent trends with depth. In general, all three aquifers are higher yielding to the south of the present course of the Selwyn River. This suggests that gravel deposits of the Selwyn River extend to depth south of the current location of the river.

Piezometric contours show that groundwater flows in a general southeasterly direction within all three aquifers. Contours for aquifer 1 indicate that the Selwyn River provides significant recharge to the shallow aquifer in its upper reaches between Coalgate and Bealey Road.

Groundwater fluctuations in shallow wells are greatest immediately adjacent to the Selwyn River which suggests the river has a significant effect on the surrounding shallow aquifer. With progressive distance from the river, fluctuations steadily decline and rainfall recharge becomes dominant. Water levels within wells close to the Waianiwaniwa River indicate that this river provides significant recharge to aquifers 1 and 2 during flood events.

Chapter Five

Groundwater Chemistry and Recharge Sources

5.1 Introduction

A water sampling programme was undertaken during the course of this investigation with samples from a number of wells and surface bodies collected and analysed for a variety of chemicals.

The main objectives of the sampling programme were:

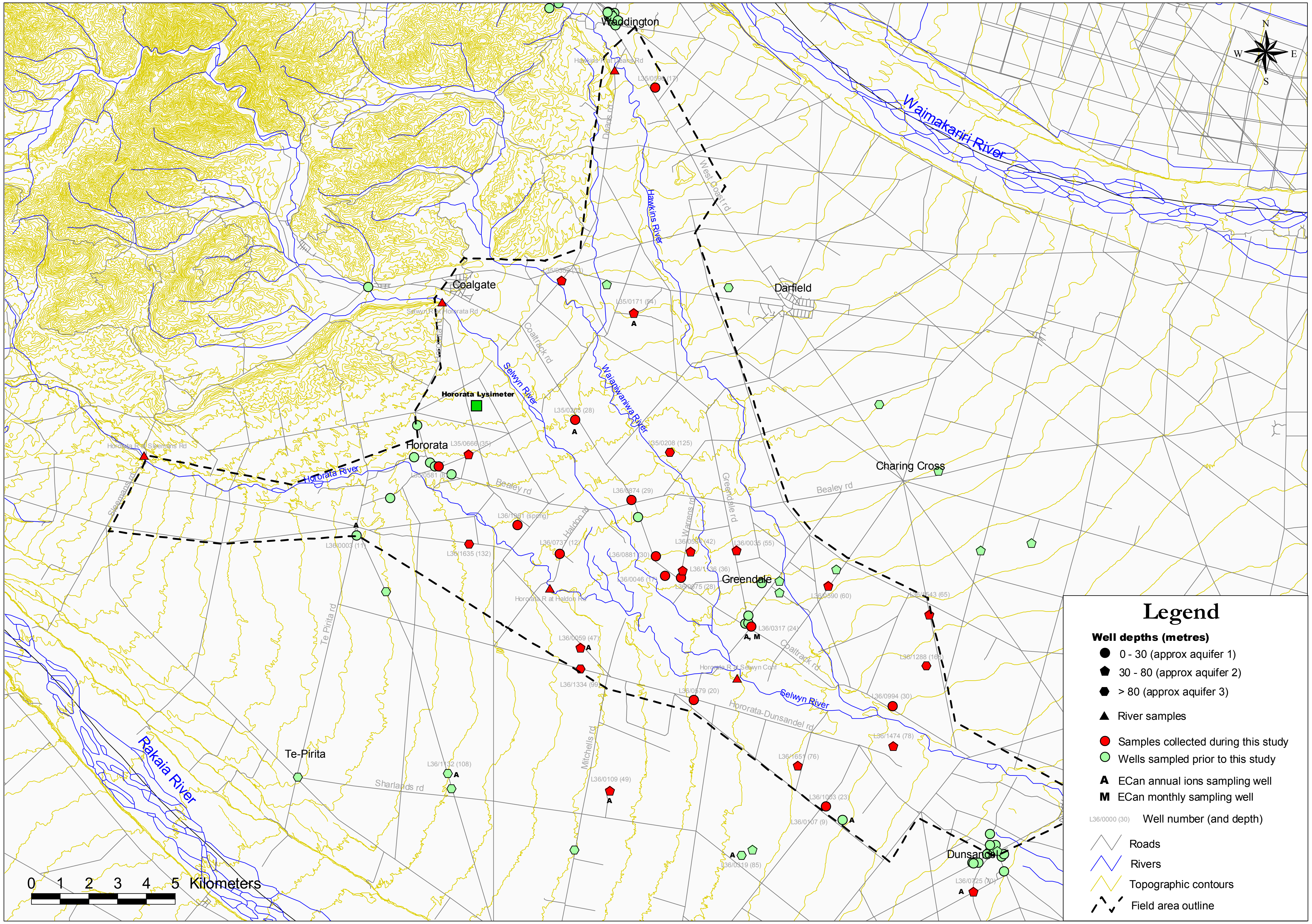
- To characterize the chemistry of groundwater in the field area and identify any trends in water chemistry both spatially and with depth
- To determine whether river recharged areas could be distinguished from rainfall recharged areas from their chemical signature and/or oxygen-18
- To compare samples to New Zealand water quality standards

The Environment Canterbury wells database revealed a number of wells in the study area had been previously sampled (Figure 5.1). Six wells in the study area are sampled once a year as part of the Environment Canterbury Annual Ions Survey. The annual ions survey takes place during September to December, and includes analyses of a broad suite of cations and anions including calcium, sodium, magnesium, potassium, iron, manganese, ammonia-nitrogen, sulphate, chloride, bicarbonate and nitrate-nitrogen. Additionally, one of these six wells (L36/0317) is part of the Environment Canterbury monthly survey. Determinands collected as part of the monthly survey include chloride, sulphate, nitrate-nitrogen and bicarbonate. Sampling frequency and determinands for the other wells vary markedly.

5.2 Chemical sampling programme

A total of 35 samples were collected during the first few weeks of February 2005 from 29 wells, 1 spring and 5 river localities (Figure 5.1). Sample sites were selected based on depth, location and objectives but were also influenced by accessibility and well log data.

Figure 5.1. Location of chemical sampling sites.



All samples were analysed for the following suite of chemicals:

- Calcium (Ca)
- Magnesium (Mg)
- Sodium (Na)
- Pottassium (K)

Major Cations

- Bicarbonate (HCO_3)
- Chloride (Cl)
- Sulphate (SO_4)
- Nitrate-Nitrogen (NO_3-N)

Major Anions

- Iron (Fe)
- Manganese (Mn)
- Bromide (Br)
- Flouride (F)
- Ammonia Nitrogen (NH_4-N)

Minor Ions

- Reactive Silica (SiO_2)

Non-ionic

Samples were analysed by Environment Canterbury's laboratory in Christchurch. In addition to the laboratory analyses pH, conductivity, temperature and dissolved oxygen were measured in the field with portable meters.

All samples were collected following the procedures outlined in the Surface Water Quality, Groundwater Quality, Biological and Habitat Assessment Field and Office Procedures Manual (Environment Canterbury, 1999).

In order to ensure that sampled well water was truly representative of the aquifer in which it resides, wells were purged by pumping a minimum of three well volumes of water prior to sampling. Conductivity, pH, temperature and dissolved oxygen were monitored and recorded in the field during purging and samples collected once these readings had stabilised. For the majority of wells installed pumps were switched on and the sample taken from as close to the wellhead as possible to avoid contamination. For wells that had no pump installed a portable submersible pump was used.

5.2.1 Water chemistry results

Results for the sampling programme are presented in Table 5.1. For all samples fluoride and bromide concentrations were equal to or below the detection limits of 0.2 mg/L and 0.05 mg/L respectively and were therefore not included in the results. Freeze and Cherry (1979) suggested ion balance errors should be less than 5% in order for the quality of the data to be considered acceptable. Two of the samples had ion balances errors of more than 5% (L36/0075, -5.3% and L36/0881, -5.5%). However, Abraham and Hanson (2004) suggest that ion balance errors of up to 10% are acceptable for the Canterbury plains aquifers because of the low ionic load of the groundwater. The ion balance errors of these two wells were thus considered acceptable for this investigation.

5.3 Water Quality

5.3.1 Drinking Water Standard Comparisons

To evaluate the quality of the water the results were compared to the 2000 Drinking-Water Standards for New Zealand (Ministry of Health, 2000). These standards outline two sets of criteria for drinking water: Guideline Values (GV's), which are based on aesthetic qualities such as smell, taste and appearance; and Maximum Acceptable Values (MAV's), which are based on the prevention of adverse health effects to humans. A summary of the Ministry of Health (2000) guideline values and maximum acceptable values are given in Appendix 5.1. In the following sections comparisons are made between the 2000 Drinking-Water-Standards.

5.3.2 pH

The Ministry of Health (2000) Drinking-Water Standards GV for pH is 7 - 8.5. pH transgressed aesthetic guidelines in 22 samples (20 wells, 1 spring and 1 river locality) with a range from 6 to 8.2 (Table 5.1). All transgressions were more acidic than the recommendations. In general, shallow rainfall recharged groundwater in Canterbury is slightly acidic. This is because rainfall itself is slightly acidic and carries carbon dioxide from plant roots and microbiological organisms into the groundwater, producing carbonic acid (Environment Canterbury, 2001). Additionally, there is little carbonate material within the aquifers to neutralize the low pH (Abraham and Hanson, 2004).

Table 5.1. Results of chemical sampling programme

Well Number	L35/0171	L35/0205	L35/0208	L35/0352	L35/0581	L35/0596	L35/0666	L36/0035	L36/0046	L36/0059	L36/0075	L36/0109	L36/0317	L36/0579	L36/0584	L36/0590	L36/0725	L36/0737	L36/0874
Depth (m)	54	28	125	33	8	17	35	55	17	47	28	49	24	20	42	60	70	12	29
pH*	6.9	6.7	7.2	6.4	6.2	7.1	7.7	6	6.6	6.8	6.3	6.9	6.4	6.6	6.7	6.5	6.2	6.4	6.4
Water Temperature (°C)*	12.9	19	15.2	15.4	12.9	12.3	12	12.4	12.6	12.1	12.6	12.5	12.3	12.2	12.8	12.2	12.2	11.7	12.6
Conductivity at 25°C (mS/m)*	11	17	14	17	15	14	11	16	20	13	23.2	15	15	12	22	17	16	11	16
Dissolved Oxygen (mg/L)*	9.2	7.1	6.9	4.1	2.5	8.4	5.7	8	7.9	6.1	8.8	5.8	5.5	6.9	7.5	6.8	6.9	8.9	9
Alkalinity (mg HCO_3/L)	39	55	60	48	41	38	54	44	46	52	45	54	48	45	50	48	60	50	44
Ammonia Nitrogen (mg/L)	0.005	<0.005	<0.005	<0.005	0.005	0.011	<0.005	0.009	0.019	0.007	0.01	0.006	0.03	0.006	0.013	0.005	0.011	0.007	0.007
Calcium (mg/L)	9.4	14	15	11	13	13	13	12	16	13	14	16	11	12	16	14	16	11	14
Chloride (mg/L)	6	8.9	7.6	13	11	6.2	4.2	9.5	10	5.9	12	7.8	7.2	5.2	13	9.7	7.6	4.6	7.7
Iron (mg/L)	<0.03	0.04	<0.03	0.11	<0.03	<0.03	<0.03	<0.03	0.08	0.03	<0.03	<0.03	<0.03	<0.03	0.07	<0.03	<0.03	<0.03	0.04
Magnesium (mg/L)	3.2	5.2	3.3	4.3	3.6	3.9	3.3	4.4	5.8	3.6	6.7	3.3	4.3	3.2	6.6	4.5	4.9	3.2	4.4
Manganese (mg/L)	<0.01	<0.01	<0.01	0.01	<0.01	0.01	<0.01	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrate-Nitrogen (mg/L)	2.4	4.7	2.2	1.5	3.7	4.8	0.9	6.2	9	2.1	10.6	3.8	4.1	1.6	11.5	6.3	4.3	1.4	5.3
Pottassium (mg/L)	1	1.2	1	1.6	1.6	1.2	1	1.5	1.5	1	1.5	0.9	1.6	0.9	1.5	1.2	1	0.8	1.4
Reactive Silica (mg SiO_2/L)	12	15	17	13	16	13	12	17	15	13	16	15	13	12	18	19	17	12	13
Sodium (mg/L)	6.6	9.6	9.3	13	11	6.9	5.7	12	12	7.1	14	7.9	10	6.3	14	12	8.9	5.9	9.5
Sulphate (mg/L)	5.4	9.2	3	16	11	8	3.8	7	12	4.5	13	4.4	6.9	4.7	5.9	6	6	4.3	9.9
Total Hardness (mg $CaCO_3$/L)**	37	57	51	45	48	49	46	48	64	48	63	54	45	43	68	54	60	41	53
Total Dissolved Solids (mg/L)***	85	123	118	122	112	95	98	114	127	102	133	113	106	91	137	121	126	93	109
Sum Anions (meq/L)	1.092	1.680	1.418	1.594	1.476	1.307	1.147	1.578	1.929	1.263	2.104	1.468	1.427	1.097	2.130	1.635	1.630	1.139	1.523
Sum Cations (meq/L)	1.044	1.572	1.448	1.508	1.461	1.300	1.193	1.518	1.835	1.278	1.892	1.435	1.377	1.158	1.986	1.618	1.612	1.088	1.508
Ion Balance (% diff)	-2.2	-3.3	1	-2.8	-0.51	-0.27	2	-1.9	-2.5	0.59	-5.3	-1.1	-1.8	2.7	-3.5	-0.52	-0.56	-2.3	-0.49
Sodium Absorption ratio	0.47	0.56	0.57	0.84	0.70	0.43	0.37	0.75	0.65	0.45	0.77	0.47	0.65	0.42	0.74	0.71	0.50	0.40	0.57

Well Number	L36/0881	L36/0994	L36/1003	L36/1136	L36/1288	L36/1334	L36/1474	L36/1543	L36/1635	L36/1651	L36/1961
Depth (m)	30	30	23	36	168	99	78	65	132	76	Spring
pH*	6.4	6.5	7	6.3	7.8	7.5	7	6.6	7.8	7.8	6.8
Water Temperature (°C)*	12	12.2	12.7	14.6	14.1	12.2	13.7	12.5	13.3	12.9	13
Conductivity at 25°C (mS/m)*	17	14	19	27	17	14	13	23	18	12	12
Dissolved Oxygen (mg/L)*	9.7	5.1	8.5	9.7	1.7	10	1.7	7.4	6.6	3.2	6.6
Alkalinity (mg HCO_3/L)	47	57	63	47	85	47	60	48	97	61	54
Ammonia Nitrogen (mg/L)	<0.005	0.047	0.062	<0.005	<0.005	0.011	<0.005	0.017	0.005	0.005	0.049
Calcium (mg/L)	12	15	18	20	18	15	13	17	16	12	12
Chloride (mg/L)	8.6	7.3	8.7	13	8.8	8.1	6.4	10	7.4	5.6	4.6
Iron (mg/L)	<0.03	0.07	<0.03	<0.03	<0.03	<0.03	0.03	<0.03	<0.03	0.04	0.06
Magnesium (mg/L)	5.2	4.1	5.4	7.8	5	3.4	3.5	4.9	6.6	3.9	3.4
Manganese (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	0.02	0.02
Nitrate-Nitrogen (mg/L)	5.9	1.9	5	15.3	1.4	4.8	1.6	7.1	0.4	1.2	1.6
Pottassium (mg/L)	1.2	1.3	1.3	1.6	1	0.9	0.9	1.3	0.9	0.8	0.9
Reactive Silica (mg SiO_2/L)	15	11	14	19	19	16	18	18	18	18	13
Sodium (mg/L)	9.6	7.4	8.7	16	10	7.2	8.1	12	12	7.6	6
Sulphate (mg/L)	10	5.6	8.4	10	2.9	1.2	1.9	7.4	1.8	1.8	4.3
Total Hardness (mg $CaCO_3$/L)**	52	55	68	83	66	52	47	63	68	46	44
Total Dissolved Solids (mg/L)***	115	111	133	150	151	104	113	126	160	112	100
Sum Anions (meq/L)	1.643	1.393	1.810	2.438	1.802	1.367	1.318	1.730	1.865	1.281	1.219
Sum Cations (meq/L)	1.472	1.444	1.756	2.371	1.767	1.364	1.310	1.804	1.882	1.269	1.166
Ion Balance (% diff)	-5.5	1.8	-1.5	-1.4	-0.98	-0.11	-0.3	2.1	0.45	-0.47	-2.2
Sodium Absorption ratio	0.58	0.44	0.46	0.77	0.54	0.44	0.51	0.66	0.64	0.49	0.39

River Samples

	A	B	C	D	E
Depth (m)					
pH*	8.2	7	7	6.6	7.2
Water Temperature (°C)*	19.8	19.2	18.1	15.1	13.9
Conductivity at 25°C (mS/m)*	10	9	12	11	11
Dissolved Oxygen (mg/L)*	nm	nm	nm	nm	8.7
Alkalinity (mg HCO_3/L)	51	41	57	50	47
Ammonia Nitrogen (mg/L)	0.12	<0.005	0.007	0.005	0.016
Calcium (mg/L)	11	6.4	13	12	9.8
Chloride (mg/L)	3.1	6.1	4.8	5	5.2
Iron (mg/L)	0.06	0.07	0.07	<0.03	0.05
Magnesium (mg/L)	2.3	1.9	3.4	3.1	3.3
Manganese (mg/L)	<0.01	<0.01	<0.01	0.01	<0.01
Nitrate-Nitrogen (mg/L)	0.1	0.1	1	0.9	1.4
Pottassium (mg/L)	0.7	1.2	1	0.9	0.8
Reactive Silica (mg SiO_2/L)	9.3	9	12	11	10
Sodium (mg/L)	5	8.4	6.2	6.4	6.8
Sulphate (mg/L)	2.8	1.3	4.2	4.8	4.9
Total Hardness (mg $CaCO_3$/L)**	37	24	47	43	38
Total Dissolved Solids (mg/L)***	85	75	103	94	89
Sum Anions (meq/L)	0.989	0.879	1.229	1.125	1.119
Sum Cations (meq/L)	0.982	0.871	1.224	1.154	1.077
Ion Balance (% diff)	-0.36	-0.46	-0.2	1.3	-1.9
Sodium Absorption ratio	0.36	0.75	0.40	0.43	0.48

Notes

[yellow] Transgressed 2000 New Zealand Drinking Water Standards (Ministry of Health, 2000) Guideline Values

[pink] Exceeds 2000 New Zealand Drinking Water Standards (Ministry of Health, 2000) Maxiumum Acceptable Values

nm = not measured

* Parameters measured in the field

** Total Hardness calculated as the sum of Calcium/0.4 and Magnesium/0.24

*** Total Dissolved Solids calculated by summing ion concentrations and reactive silica

River Sample Localities

- **A** Selwyn River at Hororata Rd
- **B** Hororata River at Sleemans Rd
- **C** Hororata River at Haldon Rd
- **D** Hororata River at Selwyn Confluence
- **E** Hawkins River at Deans Rd

The spatial distribution of pH is shown in Figure 5.2. This figure shows that the transgression of pH occurs predominantly in wells penetrating aquifers 1 and 2 (i.e. wells less than 80m deep). Most river samples and deeper wells (greater than 80m) had pH levels within the 2000 New Zealand Drinking Water Standards GV's.

Although low pH will not affect human health it is corrosive and can dissolve metals leading to erosion of pipes and pumps.

5.3.3 Nitrate-Nitrogen

The Ministry of Health (2000) Drinking-Water Standards MAV for nitrate-nitrogen is 11.3 mg/L. Nitrate-nitrogen exceeded maximum acceptable values in 2 wells (L36/1136, 15.3 mg/L and L36/0584, 11.6 mg/L), with a range from 0.4 through to 15.3 mg/L (Table 5.1).

Figure 5.3 shows the spatial distribution of the nitrate-nitrogen concentrations for the sampled wells and spring. The Ministry of Health (2000) recommend increased monitoring for those wells that exceed half of the MAV. Figure 5.3 shows an area where nitrate-nitrogen values are elevated above half of the MAV. A further map was produced showing the median values for all wells sampled for nitrate-nitrogen in the field area including this study (Figure 5.4). This figure shows that the area of elevated levels may extend further south, and identified the presence of elevated nitrate-nitrogen levels in wells in Hororata Township. Most other wells had nitrate-nitrogen concentrations below half of the MAV.

Although nitrate-nitrogen occurs naturally in groundwater it is generally only in low concentrations. Madison and Brunett (1985) suggested concentrations greater than 3 mg/L are indicative of contamination from anthropogenic sources such as fertiliser application or waste disposal whilst Burden (1980) suggested concentrations greater than 1 mg/L do not occur naturally in New Zealand aquifers. The source of the main area of elevated concentrations appears to originate in the shallow to second aquifer near the intersection of Coaltrack Road and Warrens Road. Downstream, concentrations are elevated in progressively deeper wells. These patterns indicate southeast movement and downwards percolation of nitrate-nitrogen from the source area. Farming practices upstream of the source area are dominantly crop and sheep and it is likely that the high nitrate-nitrogen elevations in this area are the cumulative result of fertiliser application upgradient of the source. Transmissivity values show that groundwater travels very

Figure 5.2. Distribution of pH, conductivity and dissolved oxygen for sampled wells, spring and river localities

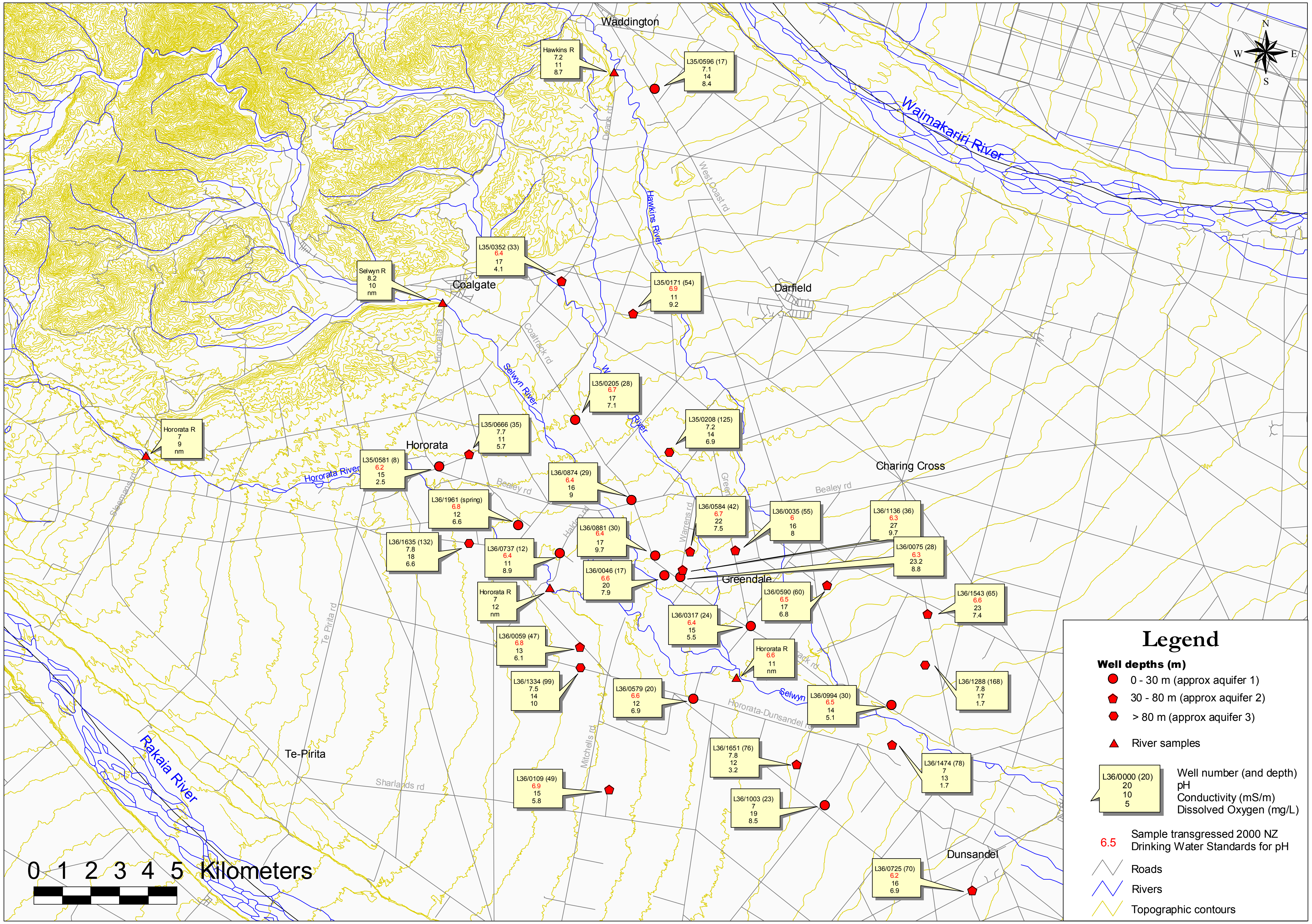


Figure 5.3. Distribution of nitrate-nitrogen for samples collected during this study

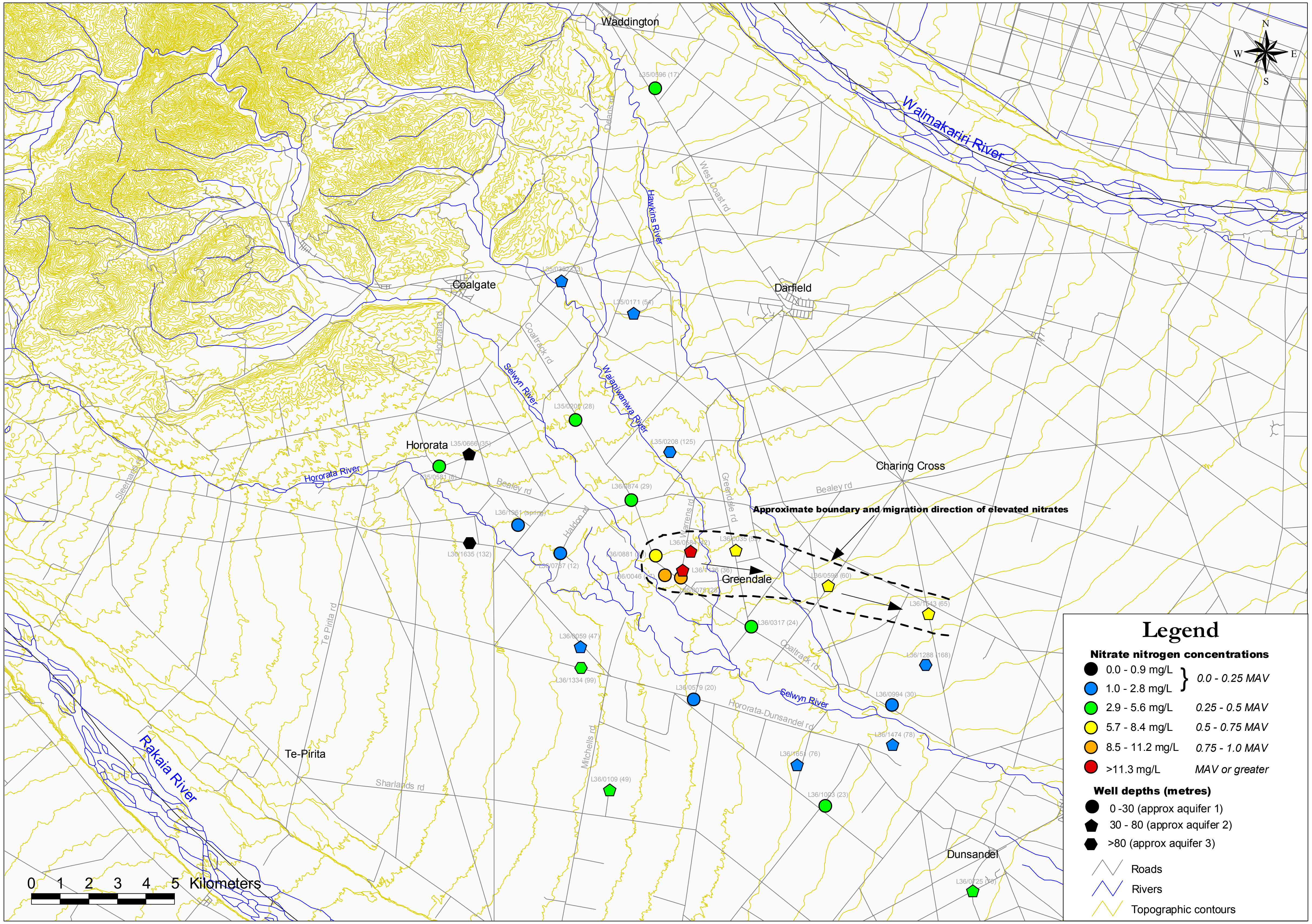
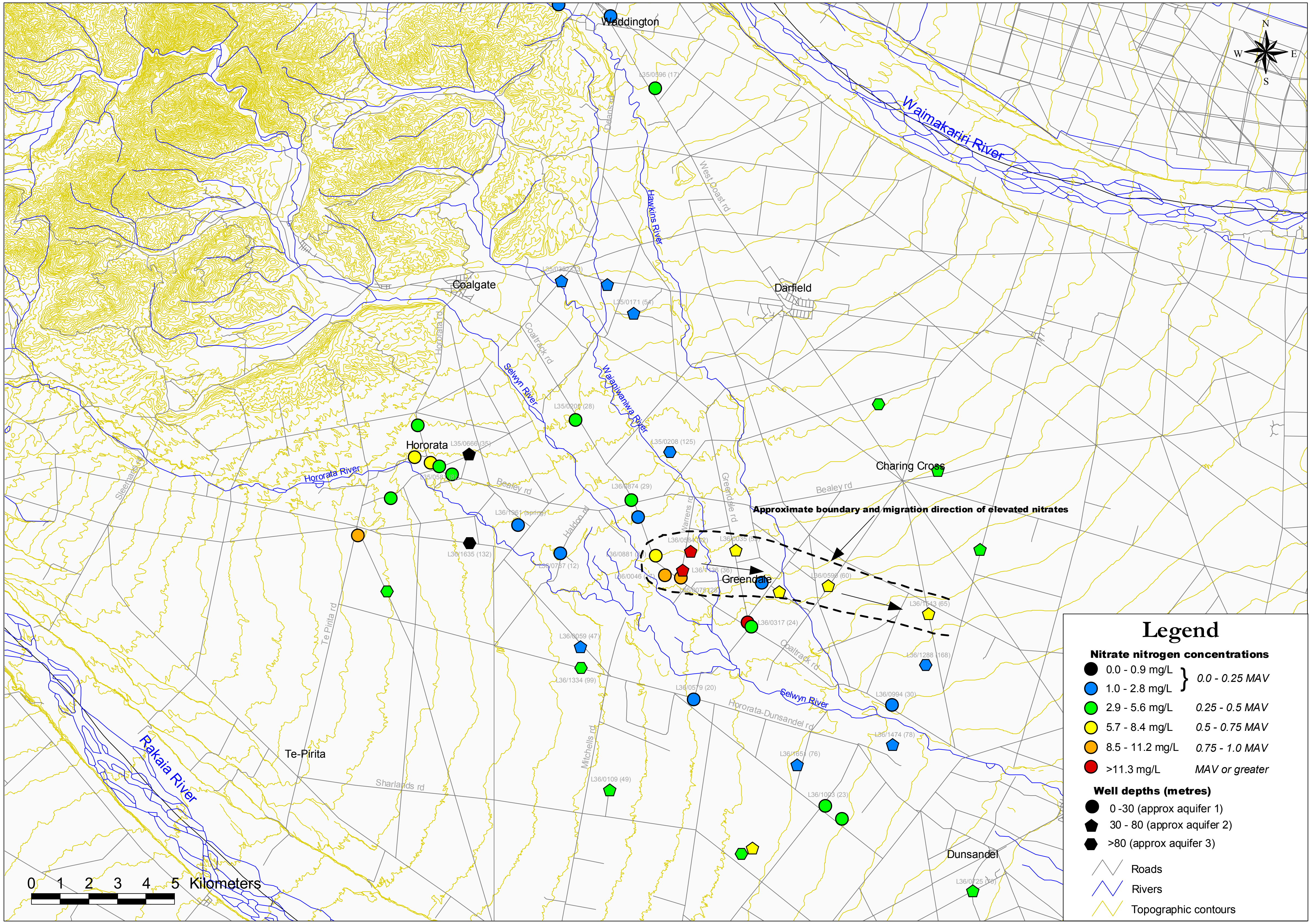


Figure 5.4. Distribution of nitrate-nitrogen for all wells sampled previously and/or during this study



slowly in the area of elevated nitrates. It is possible that groundwater is encountering relatively impermeable overbank deposits of the Waianiwaniwa River at depth, which flows at a considerable angle to the Selwyn River near this area, which is decreasing groundwater flow. Alternatively, elevated nitrates may be related to a nearby thrust fault (figure 2.9 – back pocket).

Nitrate-nitrogen was also elevated in two shallow wells (less than 24 metres) on the corner of Greendale Road and Coaltrack Road (Figure 5.4). Hanson (2002) suggested these concentrations are local and caused by leakage from an upgradient septic source. It is therefore unlikely that these wells are an extension of the main area of elevated concentrations. Similarly, the higher concentrations in Hororata Township are only associated with very shallow wells (less than 10 metres) and are likely to be related to local septic tank contamination.

Nitrate-nitrogen concentrations in all wells deeper than 70 m were less than half of the MAV. Hanson (2002) suggested deeper aquifers have lower nitrate concentrations because of a reduction in oxidation potential with depth and distance from the source.

5.3.4 Total Hardness

Total hardness is a measure of how much calcium and magnesium is present in the water. In general terms the hardness of a water can be defined as the ease with which soap can be lathered up in that water. Soap is easily lathered up in soft water but difficult to lather in hard water. Water can be classified as soft, moderately hard, hard or very hard depending on the concentration of $CaCO_3$ in mg/L (Table 5.2). Total hardness tends to be higher in shallow rainfall-derived groundwater because rainfall on passage through the soil transports soluble ions including calcium and magnesium into the groundwater (Hayward, 2002).

Classification	**Hardness range (mg/L of $CaCO_3$)**
Soft	0 - 60
Moderately hard	61 - 120
Hard	121 – 180
Very hard	>180

Table 5.2 Total Hardness Classification (from Hem, 1992)

The spatial distribution of hardness is shown in figure 5.5. All waters can be classified as soft or moderately hard water. Figure 5.5 shows that moderately hard water occurs in wells penetrating aquifer 3 (L36/1635 and L36/1288) and in shallower wells (less than 42 m deep) on the corner of Coaltrack Road and Warrens Road. The latter wells also have high nitrate-nitrogen concentrations which suggest that area is dominantly rainfall recharged.

Although hardness does not pose any health risks hard water can cause scale development on the inside of pipes and soft water can corrode metals because it tends to be slightly acidic.

5.3.5 Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS), which are the total amount of solids in mg/L, that remain when a water sample is evaporated to dryness, provide a good basic measure of water quality (Fetter, 2001). Water can be classified into four groups depending on the TDS concentration (Table 5.3).

Classification	**Total Dissolved Solids (mg/L)**
Fresh water	0 – 1,000
Brackish water	1,000 – 10,000
Saline water	10,000 – 100,000
Brine water	> 100,000

Table 5.3 Total Dissolved Solids Classification (from Freeze and Cherry, 1979).

The spatial distribution of TDS is shown in figure 5.6. All waters can be classified as fresh water. Figure 5.6 shows there is a general trend of increasing TDS with increasing depth and/or increased nitrate-nitrogen concentrations. The increase in TDS with depth reflects a general increase in groundwater residence times and an associated increase in mineral reactions.

5.3.6 Cations

Pie charts showing the relative concentrations of the major cations, in milliequivalents per litre (meq/L), are presented in figure 5.7. In most samples calcium is the dominant cation with magnesium and sodium also occurring in significant concentrations. Potassium has low concentrations in all samples and this is because potassium is easily removed from solution during reactions within the soil zone and/or aquifer material (Rosen, 2001). Total cation

Figure 5.5. Geographic distribution of hardness for sampled wells.

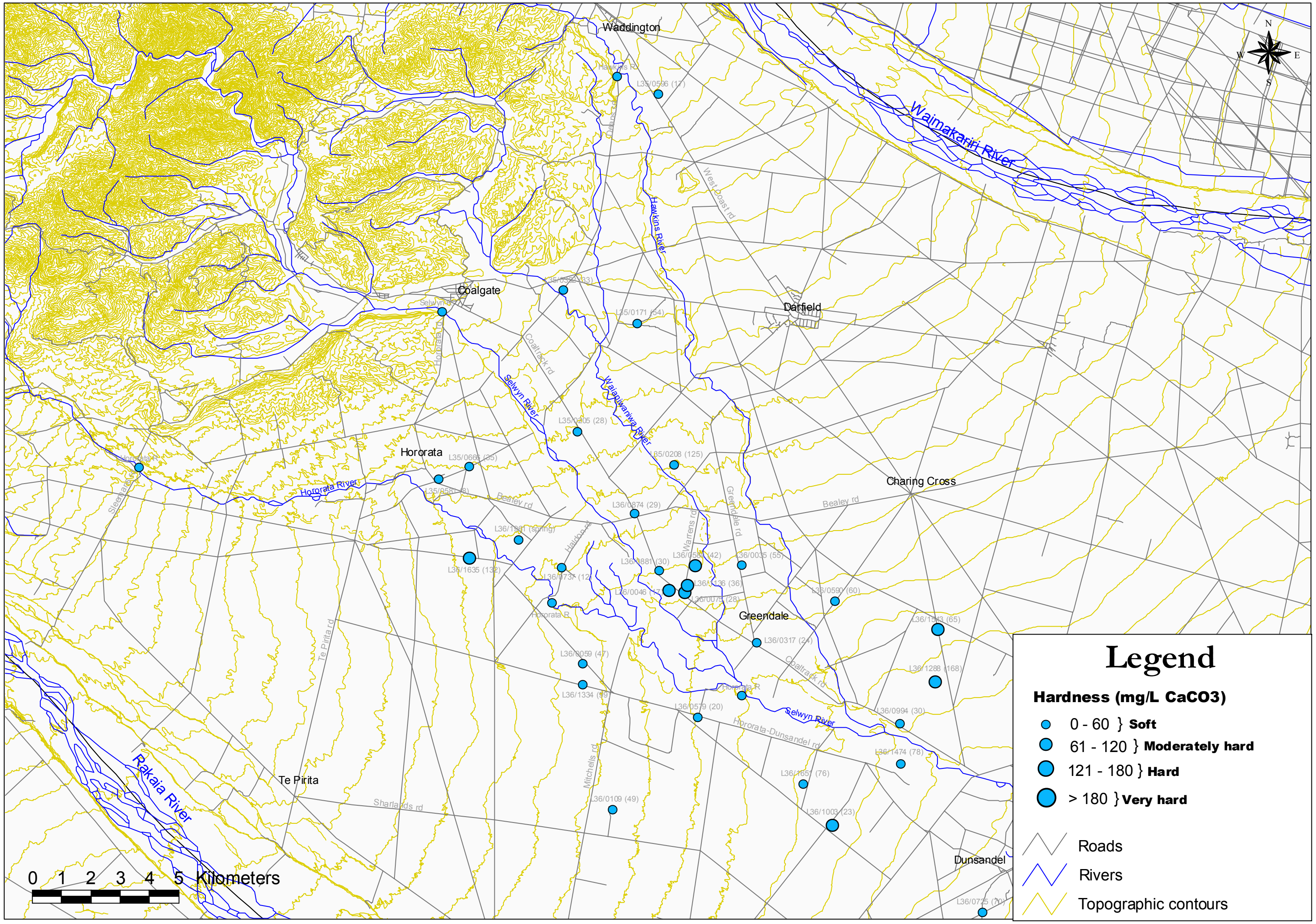


Figure 5.6. Geographic distribution of total dissolved solids for sampled wells.

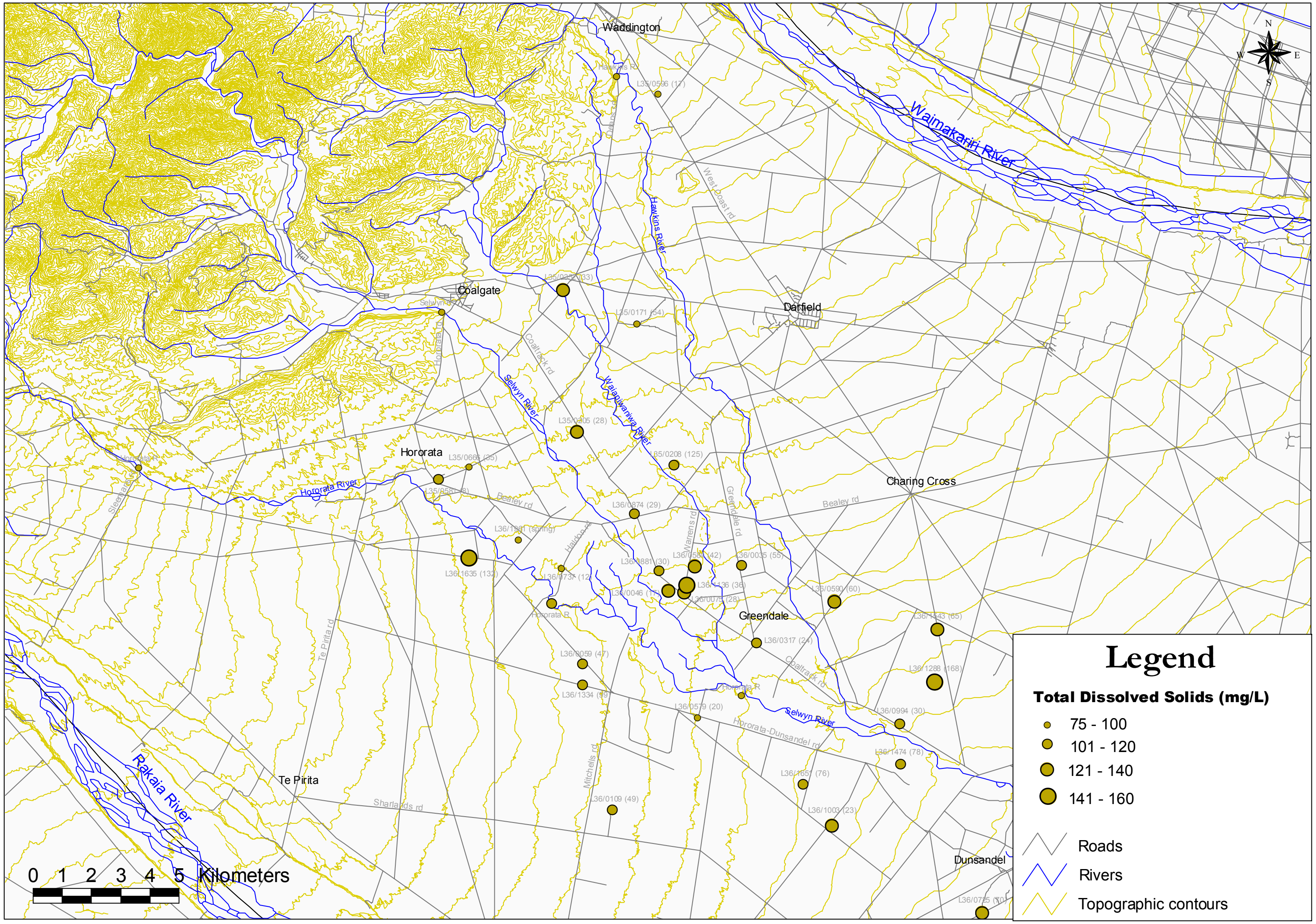
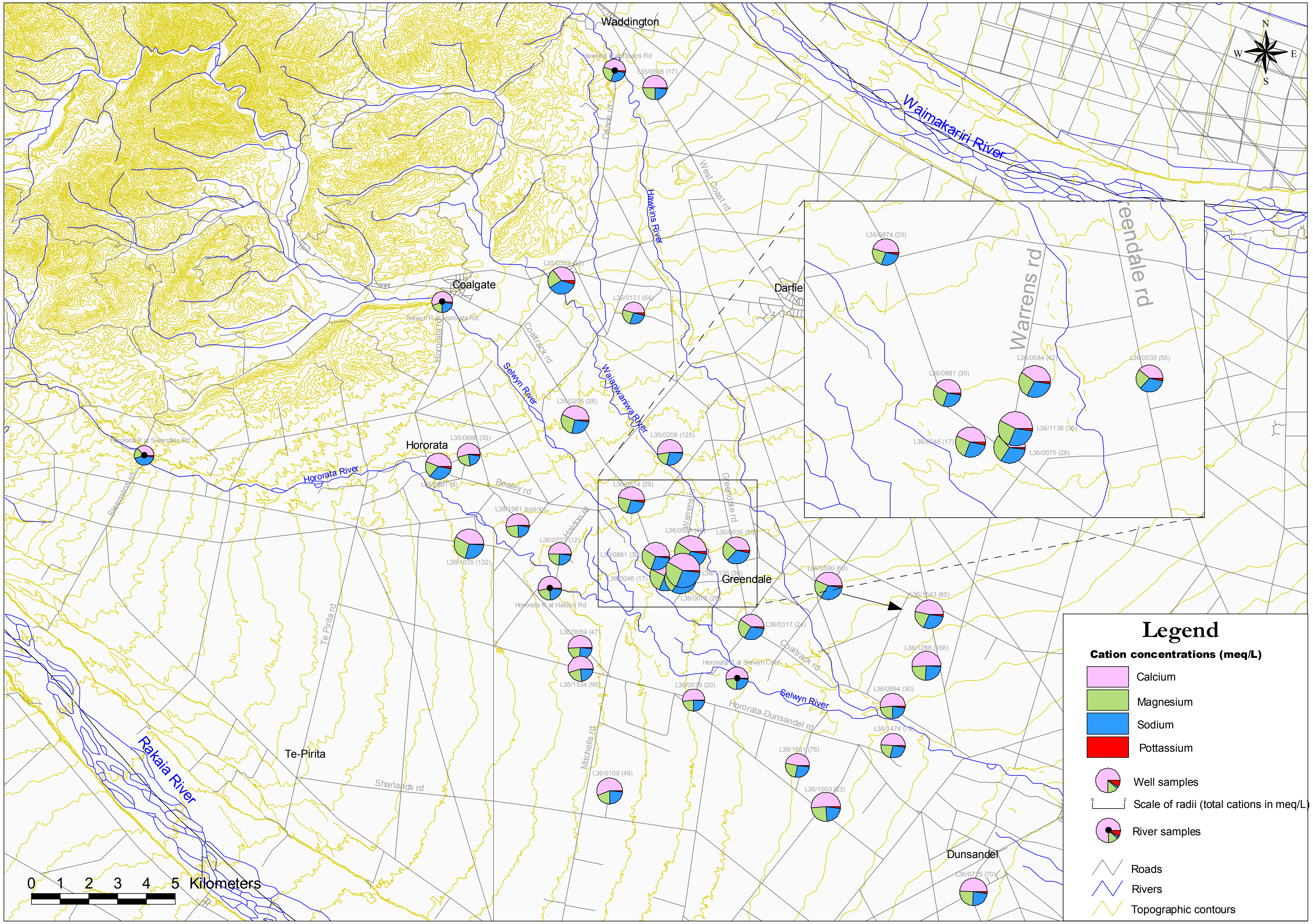


Figure 5.7. Pie charts showing relative abundance of cations (in meq/L) for sampled wells, spring and river localities



concentrations are greater in aquifer 3 (L36/1635 and L36/1288) and in shallower wells north of the Selwyn River. Wells near the corner of Coaltrack Road and Warrens Road in which nitrate-nitrogen concentrations were elevated (L36/0881, L36/0046, L36/0075, L36/1136, L36/0584) tend to have higher magnesium and sodium concentrations. This is not easily discernable in figure 5.7 but can be seen in Table 5.1. The higher concentrations of magnesium and sodium in these wells, is probably due to the application of fertilisers to the soil.

5.3.7 Anions

Pie charts showing the relative concentrations of the major anions, in meq/L, are presented in figure 5.8. In most samples bicarbonate is the dominant anion. Chebotarev (1955) showed that anion concentrations in groundwater tend to evolve from a bicarbonate dominance in young, shallow groundwater to chloride dominance in older water in a sequence known as the Chebotarev sequence (Figure 5.9).

Travel along flow path ——————▶
HCO_3 ——▶ $HCO_3 + SO_4$ ——▶ $SO_4 + HCO_3$ ——▶ $SO_4 + Cl$ ——▶ $Cl + SO_4$ ——▶ Cl
Increasing age ——————————————▶

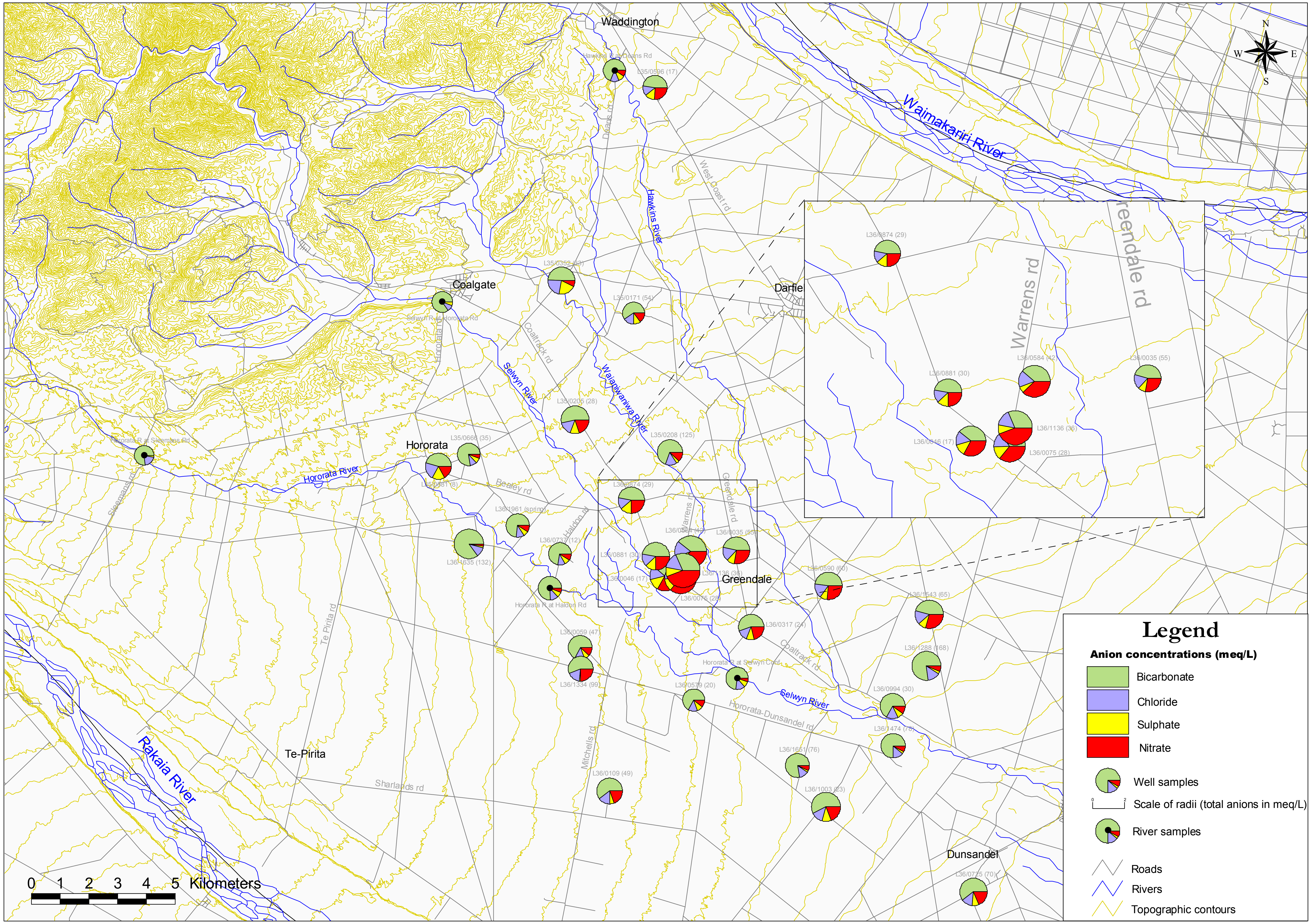
Figure 5.9 Chebotarev sequence showing relative abundance of anions for groundwater (from Freeze and Cherry, 1979).

Completion of the sequence is dependant not only on age and travel time but also on the availability and solubility of certain minerals within the aquifer (Chebotarev, 1955).

Rosen (2001) and Hayward (2002) suggest that most groundwaters in New Zealand rarely evolve past the HCO_3 stage. This is because most aquifers in New Zealand are lacking in soluble minerals. Aquifers of the Canterbury Plains are dominated by greywacke which is composed largely of silica. Silica is non-ionic and as a result mineral interactions between silica and ions are limited. Table 5.1 shows that silica represents a major component of the TDS of the samples, reflecting the dominantly greywacke aquifer material.

All wells showed a dominance of bicarbonate over sulphate and chloride indicating little evolution along the Chebotarev sequence. However, two deeper wells (L36/1635 and L36/1288) have significantly higher bicarbonate concentrations than the other wells. These wells also have very low sulphate concentrations. It is likely that these two wells are more evolved along the

Figure 5.8. Pie charts showing relative abundance of anions (in meq/L) for sampled wells, spring and river localities



chebatarev sequence with the increased bicarbonate the result of greater residence times (and reactions) and the absence of SO_4 probably due to sulphate reduction at depth (Rosen, 2001).

Figure 5.8 shows that total anion concentrations reflect those of the cations with higher concentrations in the deeper aquifer (L36/1635 and L36/1288) and in shallower wells north of the Selwyn River.

Wells with higher concentrations of nitrates also have higher concentrations of chloride and sulphate. Although not easily discernable in figure 5.8, this trend can be seen in table 5.1 and probably reflects a dominance of rainfall recharge in areas of high nitrates.

5.3.8 Conductivity and Dissolved Oxygen

The spatial distribution of conductivity and dissolved oxygen (DO) can be seen in figure 5.2. Conductivity is a measure of how electrically conductive a water is. In general, conductivity values increased with higher nitrate-nitrogen concentrations (figures 5.3 and 5.4) and/or with higher TDS content (Figure 5.6).

Dissolved oxygen is a measure of the amount of oxygen present in water. In general, dissolved oxygen concentrations in groundwater decrease with distance and depth from the recharge (oxygen) source (Freeze and Cherry, 1979). As water enters the groundwater system the dissolved oxygen is consumed by any organic matter within the aquifer at a rate which is dependant on the amount of organic matter present. No apparent trends in DO both spatially and with depth could be discerned (Figure 5.2).

5.3.9 Iron and manganese

All samples had very low concentrations of iron and manganese. Iron values ranged from less than the detection limit of 0.03 mg/L to 0.11 mg/L whilst manganese values ranged from less than the detection limit of 0.01 mg/L to 0.03 mg/L (Table 5.1). Iron and manganese are generally only abundant in significant quantities if oxygen is not abundant in solution. The reasonably high dissolved oxygen and low ammonia nitrogen relative to nitrate nitrogen in all well samples suggest an oxygen-rich aquifer environment.

5.3.10 Sodium Absorption Ratio (SAR)

The Sodium Absorption Ratio (SAR) is a useful method for evaluating the suitability of groundwater for irrigation and is calculated from the following equation:

$$SAR = \frac{Na}{((Ca + Mg)/2)^{0.5}}$$

where sodium, calcium and magnesium are in milliequivalents per litre (meq/L).

When sodium-rich water is applied to a soil, some of the sodium is taken up by the clay in the soil. The clay then gives up calcium and magnesium in exchange. This reaction can alter the physical characteristics of the soil by reducing the permeability of the soil when wet, and increasing the hardness of the soil when dry causing damage to the soil structure (Driscoll, 1986). The suitability of water for irrigation is shown in Table 5.4.

Sodium absorption ratio	**Irrigation hazard**
0 – 10 (but preferably under 2)	Little danger from sodium (good irrigation water)
7 – 18	Medium hazards from sodium
11 – 26	High hazards from sodium
>26	Very high hazards from sodium (bad irrigation water)

Table 5.4 Sodium Absorption Ratio and irrigation hazard classification (from Fetter, 2001).

The SAR for all samples was less than 1, indicating little danger from sodium and good irrigation water.

5.4 Seasonal variations in water chemistry

Seasonal variations in water chemistry are largely controlled by variations in recharge source but may also be affected by land use changes throughout the year (Hayward, 2002). Chloride, nitrate-nitrogen and sulphate concentrations for Environment Canterburys monthly monitoring well L36/0317 (24m deep) are shown in figure 5.10. Concentrations show distinct seasonal fluctuations with strong correlations between each chemical.

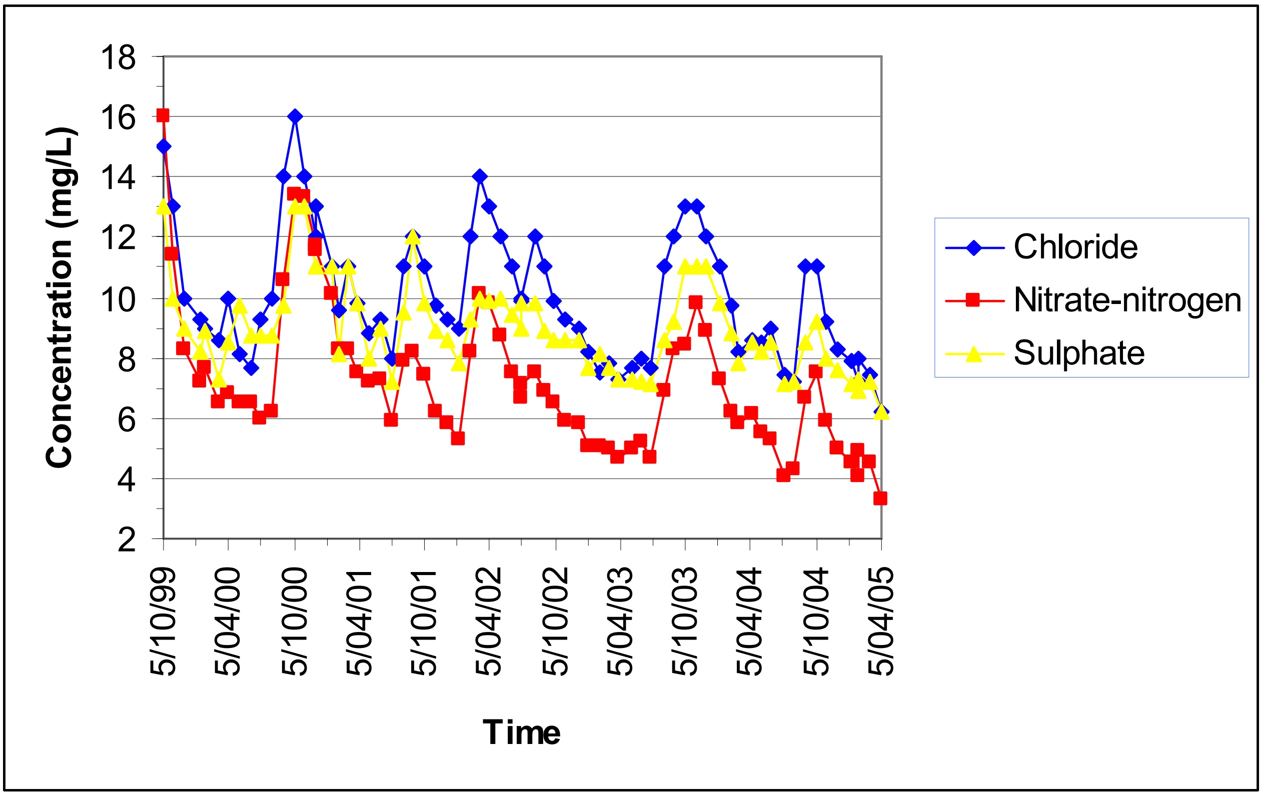


Figure 5.10 Chloride, nitrate-nitrogen and sulphate concentrations (mg/L) with time for well L36/0317.

In general, concentrations of all three chemicals increased during winter and spring months (July to December). A possible explanation for these fluctuations is that during these months rainfall is high and evaporation rates are low which results in higher soil moisture and greater downward percolation which would carry chemicals in greater quantities to the aquifers. This pattern of fluctuations is only likely to be seen in shallow wells. Concentrations in deeper wells are more smoothed out (more constant) and fluctuations are likely to be delayed due to the greater depth and thus time for recharge to percolate through to the aquifer.

5.5 Hydrochemical facies

There are various methods, both graphical and non-graphical, which can be used to identify different water types or "hydrochemical facies" based on the concentrations of the various ions.

One graphical method is the trilinear or piper diagram (Piper, 1944). The major cations (Ca, Mg, Na + K) and anions (HCO_3 + CO_3, Cl, SO_4) are plotted as percentages of their equivalent weights (meq/L) on triangles to form a point. Each cation and anion point is then projected onto a diamond-shaped field until the points intercept. This point of interception determines the hydrochemical facies. Samples collected as part of this study were projected onto a piper diagram as shown in figure 5.11. This figure shows that all waters can be classified as either calcium-bicarbonate or no dominant cation-bicarbonate waters. No observable trends between position on the piper diagram and well depth and/or location could be distinguished.

A simple non-graphical method of determining hydrochemical facies is that used by Rosen (2001) to classify New Zealand groundwaters. The major cations (Ca, Mg, Na, K) and anions (HCO_3,CO_3, Cl, SO_4) are converted to their weights in milliequivalents per litre. These weights are then converted to percentages and the hydrochemical facies determined by listing the ions greater than 10% in decreasing order (cations are listed first). Table 5.5 shows that the water can be classified into nine different hydrochemical facies using this technique.

Well numbers and river locations	**Hydrochemical facies**
L36/0035, L36/0046, L36/0317, L36/0584, L36/0590, L36/0874, L36/1334, L36/1543	Ca-Na-Mg-HCO_3-NO_3
L35/0666, L36/0725, L36/0737, L36/0994, L36/1635, L36/1961, Hororata River at Haldon rd	Ca-Mg-Na-HCO_3
L35/0171, L36/0059, L36/0579, L36/1288, L36/1474, L36/1651, Selwyn River at Hororata rd, Hororata River at Selwyn conf, Hawkins River at Deans rd	Ca-Na-Mg-HCO_3
L35/0205, L35/0596, L36/0881, L36/1003	Ca-Mg-Na-HCO_3-NO_3
L36/0075, L36/1136	Ca-Na-Mg-NO_3-HCO_3
L35/0208, L35/0109	Ca-Na-HCO_3
L35/0581	Ca-Na-Mg-HCO_3-Cl
L35/0352	Na-Ca-Mg-HCO_3-Cl-SO_4
Hororata River at Sleemans rd	Na-Ca-HCO_3

Table 5.5 Classification of groundwater into hydrochemical facies based on 'equivalents' method used by Rosen (2001).

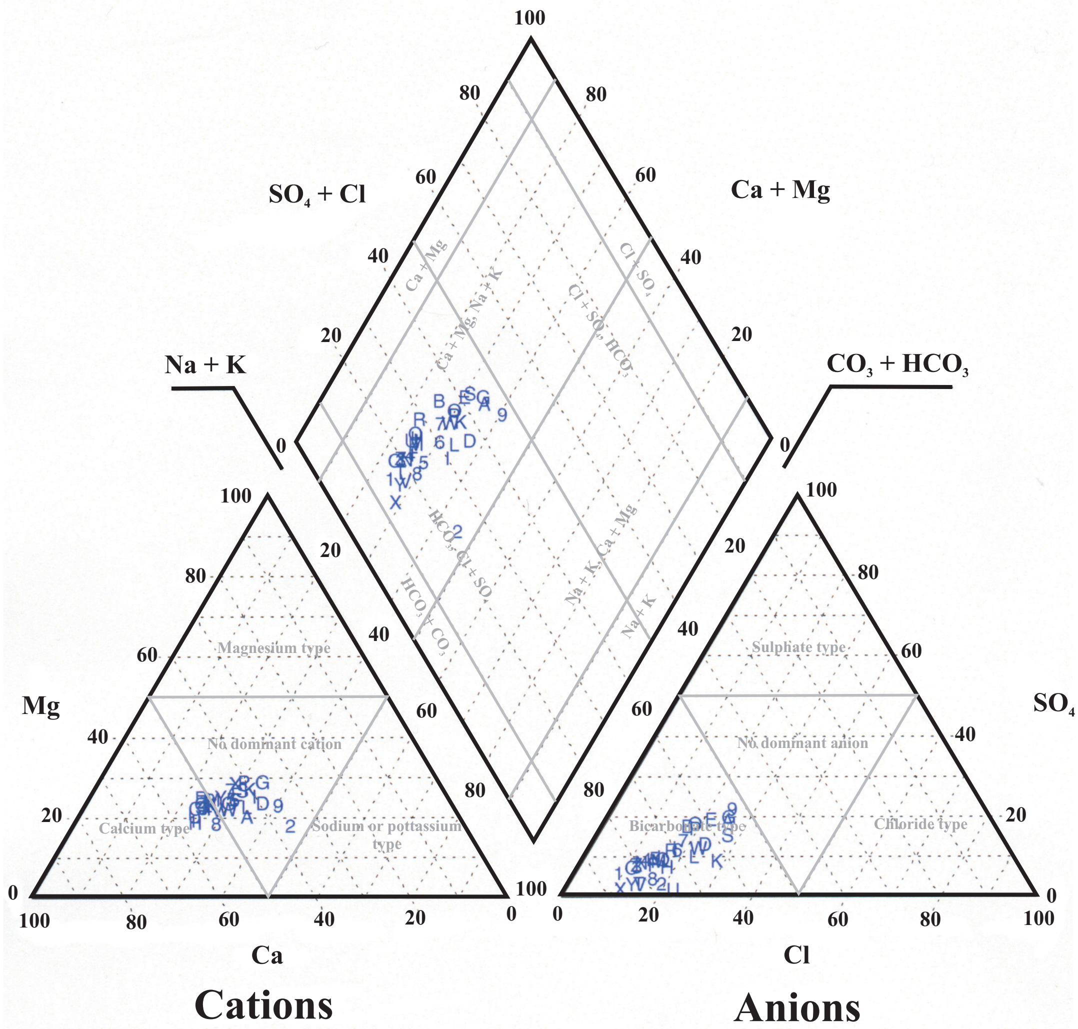
5.6 Groundwater recharge sources

An understanding of groundwater recharge sources is a necessary component for the sustainable management of the groundwater resource. River and rainfall recharged groundwater may be distinguished from water chemistry and/or oxygen-18.

5.6.1 Methodology

5.6.1.1 Water chemistry

Figure 5.11. Piper diagram for sampled wells, spring and river localities



River sample labels

1 Selwyn river at Hororata rd
2 Hororata river at Sleemans rd
3 Hororata river at Haldon rd
4 Hororata river at Selwyn confluence
5 Hawkins river at Deans rd

Well sample labels

6 L35/0171	**G** L36/0075	**Q** L36/0994
7 L35/0205	**H** L36/0109	**R** L36/1003
8 L35/0208	**I** L36/0317	**S** L36/1136
9 L35/0352	**J** L36/0579	**T** L36/1288
A L35/0581	**K** L36/0584	**U** L36/1334
B L35/0596	**L** L36/0590	**V** L36/1474
C L35/0666	**M** L36/0725	**W** L36/1543
D L36/0035	**N** L36/0737	**X** L36/1635
E L36/0046	**O** L36/0874	**Y** L36/1651
F L36/0059	**P** L36/0881	**Z** L36/1961

In general, the chemical composition of shallow groundwater derived from river and rainfall recharge is different. Rainfall reacts with minerals and nutrients on passage through the soil, resulting in enrichment of a number of ions including magnesium, calcium and chloride. The degree of enrichment will largely reflect the soil type and land use activities (Stewart et al, 2002). Chloride, in particular, is strongly enriched on passage through the soil. This enrichment is evident in soils at the Hororata Lysimeter which is located within the upper plains of the field area (Stewart, 2005) (Figure 5.1). At this site rainfall is enriched from an average value of 3.72 mg/L to an average of 16.40 mg/L on drainage through 80 cm of soil (Table 5.6). Nitrate-nitrogen concentrations are generally higher in rainfall-recharged groundwater because of the interaction of rainfall with nitrates in the soil. However, nitrate-nitrogen concentrations can be site-specific.

	Rainfall					Soil Drainage				
Year	**Amount**	**$\delta^{18}O$**	**Cl**	**NO_3-N**		**Amount**	**$\delta^{18}O$**	**Cl**	**NO_3-N**	**Period**
	mm	**‰**	**mg/l**	**mg/l**		**mm**	**‰**	**mg/l**	**mg/l**	**Sampled**
1999	495.9	-8.54				216.3	-9.03			6 months
2000	882.8	-8.84	2.88	<.02		408.3	-9.69	8.06	0.05	12 months
2001	728.0	-7.02	2.40	<.03		269.5	-6.92	20.61	0.68	12 months
2002	532.5	-8.58	3.30	<.03		46.9	-8.28	4.74	<.03	12 months
2003	741.4	-7.84	2.27	<.03		229.8	-7.25	28.04	2.11	12 months
2004	577.4	-8.67	8.89	0.0		108.0	-8.05	17.68	1.76	12 months
Means	**692.4**	**-8.17**	**3.72**	**<.03**		**212.5**	**-8.23**	**16.40**	**0.83**	

Table 5.6 $\delta^{18}O$, Chloride and nitrate-nitrogen data for direct rainfall and rainfall recharge (soil drainage at 80cm depth) at the Hororata Lysimeter site (from Stewart, 2005). Samples are taken monthly.

In contrast, river-recharged groundwater has lower ionic concentrations, including lower chloride, because it largely bypasses the soil profile. Nitrate-nitrogen concentrations are also generally low because the rivers themselves contain low concentrations. Additionally, flow rates in river-derived groundwater tend to be high, which results in dilution and dispersion of contaminants present in the water.

In addition to recharge sources the chemical composition of groundwater can also be influenced by other factors such as aquifer material, residence times and contamination. These factors must also be considered when determining recharge sources. However, the similarity of aquifer material (mostly greywacke) over the field area implies that groundwater chemistry is unlikely to be significantly affected by this factor. Also, there is little exchange of chloride within

Canterbury plains aquifers which means chloride concentrations are especially useful in distinguishing recharge sources.

5.6.1.2 Oxygen-18 (^{18}O)

Oxygen exists as two naturally occurring stable isotopes: oxygen-16 and oxygen-18. Oxygen-18 is slightly heavier and during evaporation and condensation processes fractionates relative to the lighter oxygen-16 (Taylor et al, 1989). The result is that high altitude rainfall has a more depleted (more negative) oxygen-18 concentration compared to low altitude rainfall. Rivers draining higher catchments transport this water with depleted oxygen-18 to the aquifers. These properties enable the identification of high catchment river recharged groundwater from lowland rainfall recharged groundwater. Oxygen-18 in water is expressed as $\delta^{18}O$ in units of parts per thousand (‰) by the equation:

$$\delta\ (‰) = \frac{R_{sample}}{R_{VSMOW} - 1} \times 1000$$

where R is the ratio $^{18}O/^{16}O$ and VSMOW is Vienna Standard Mean Ocean Water (Clark and Fritz, 1997).

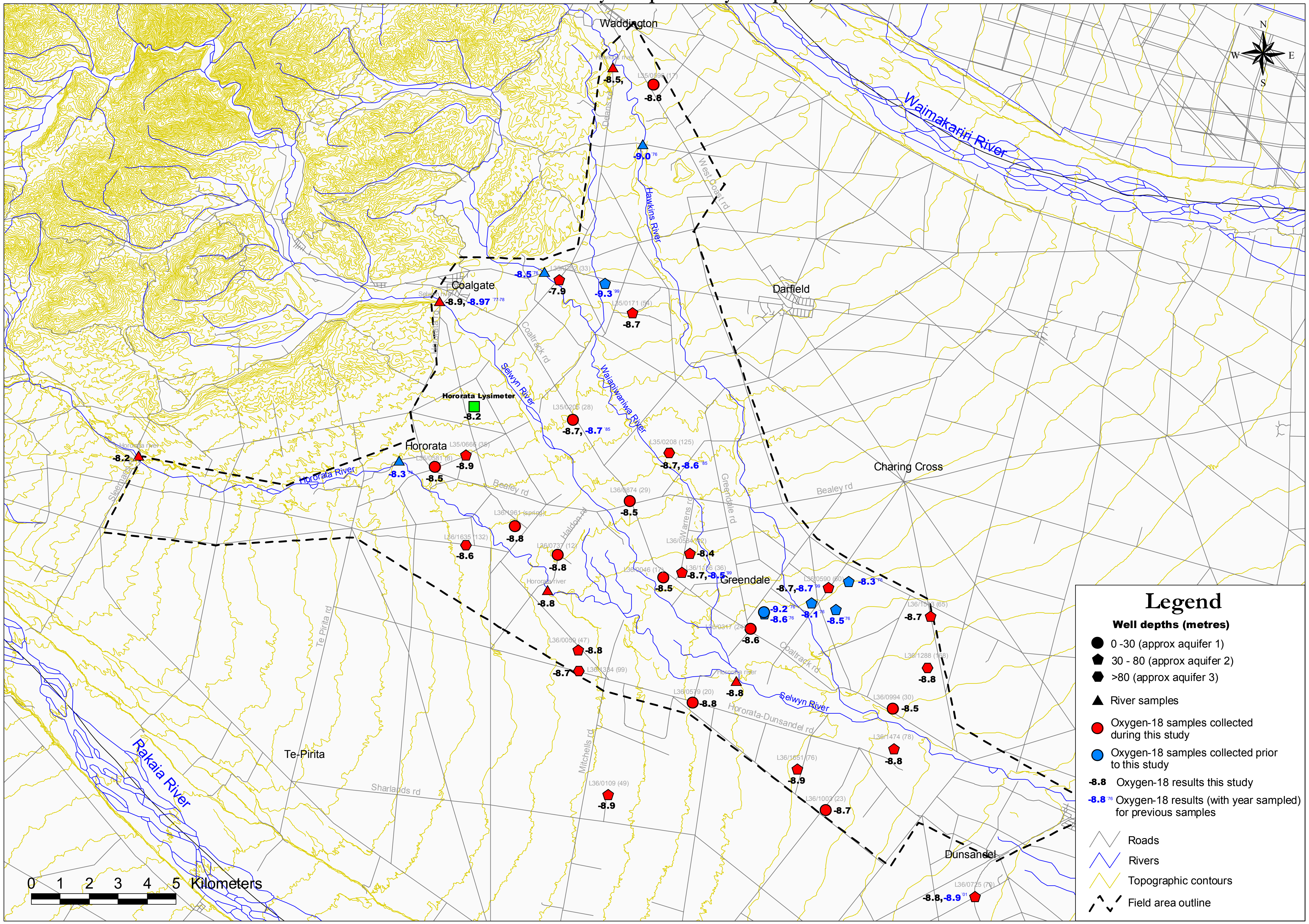
Standard measurement errors for $\delta^{18}O$ are about 0.1‰ (Stewart and Morgenstern, 2001).

5.6.2 Oxygen-18 Sampling Programme

Oxygen-18 was sampled for 26 wells, 1 spring and 5 river localities (figure 5.12) to help identify groundwater recharge sources. All of the oxygen-18 samples were also analysed for water chemistry. Samples were analysed at the Institute of Geological and Nuclear Sciences (GNS), Wellington, New Zealand.

Oxygen-18 has been periodically measured in waters of the Canterbury plains since the late 1960s (Stewart et al, 2002). The Hawkins, Waianiwaniwa and Hororata rivers along with a number of wells within the field area had been previously sampled once before for oxygen-18 (figure 5.12). The Selwyn River, together with the Rakaia and Waimakariri rivers, were sampled for oxygen-18 regularly (at least weekly) between September 1977 and June 1998.

Figure 5.12. Location and oxygen-18 results for all wells, springs and river localities sampled within the field area (includes samples collected during this study and previously sampled).



The results of the oxygen-18 sampling programme, together with the results of previous samples, are also shown in figure 5.12. The results for the Selwyn, Rakaia and Waimakariri rivers are shown in graph form in figure 5.13 and the raw data in Appendix 5.2.

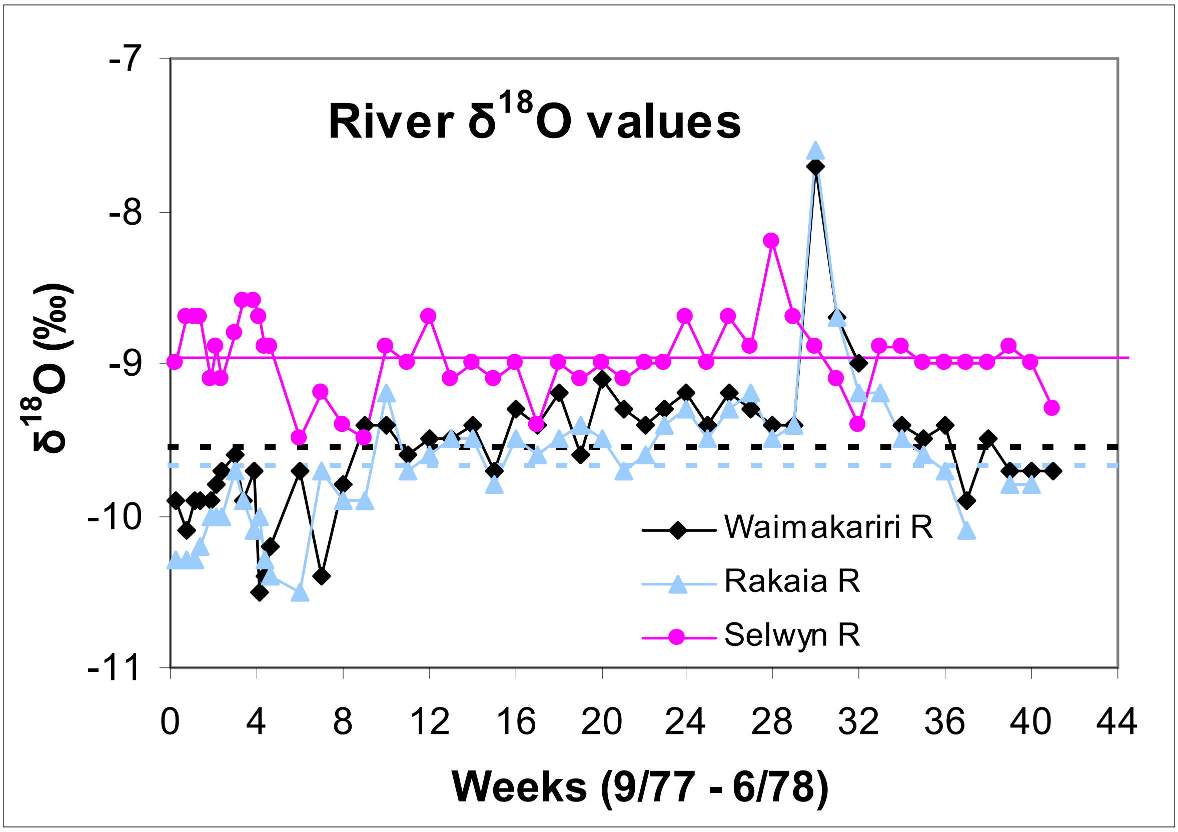


Figure 5.13 $\delta^{18}O$ results for the Waimakariri, Rakaia and Selwyn rivers sampled weekly between September 1977 to June 1978.

5.6.3 Previous applications of chemistry and Oxygen-18 for determining groundwater recharge sources within the Canterbury Plains

Water chemistry and oxygen-18 have been used successfully in the past to differentiate between rainfall and major river recharge within the Canterbury plains. This is largely based on the observations that the major rivers have a much more negative oxygen-18 signature than that of rainfall on the plains. Taylor et al (1989) estimated average $\delta^{18}O$ values for the Waimakariri and Rakaia rivers of approximate -9.4‰ and -9.5‰ respectively. The $\delta^{18}O$ values for rainfall recharge are less well restrained and Stewart et al (2002) suggested $\delta^{18}O$ values for rainfall in the inland plains of less than -9.0‰ gradually decreases to values of about -7.7‰ towards the coast.

Hayward (2002) and Stewart et al (2002) showed a gradual increase in chloride and nitrate concentrations with increasing dominance of rainfall recharge. Hayward (2002) further showed that chloride concentrations in groundwater recharged by rainfall in the Christchurch-West Melton area of the Canterbury plains tended to be within 10 – 20 mg/L. The Christchurch-West Melton area is northeast and more coastal than the study area of this research (Appendix 5.3). Stewart et al (2002) predicted that chloride concentrations in rainfall-recharged groundwater would gradually decrease with increasing distance from the coast because of the effects of "rainout" of sea-salt nuclei.

These same principles (above) apply in distinguishing Selwyn River recharge from plains rainfall recharge. However, $\delta^{18}O$ values for the Selwyn River are significantly less than that of the major rivers, with Stewart et al (2002) estimating an average value of about -8.7‰. Data from the Hororata Lysimeter (Table 5.6) show that for the five year period 2000-2004 rainfall recharge (soil drainage at 80cm depth) in the Lysimeter has average values of -8.2‰ and 16.4 mg/L for $\delta^{18}O$ and chloride respectively but with strong variations from year to year (-6.9‰ to -9.7‰ for $\delta^{18}O$ and 8 mg/L to 28 mg/L for chloride).

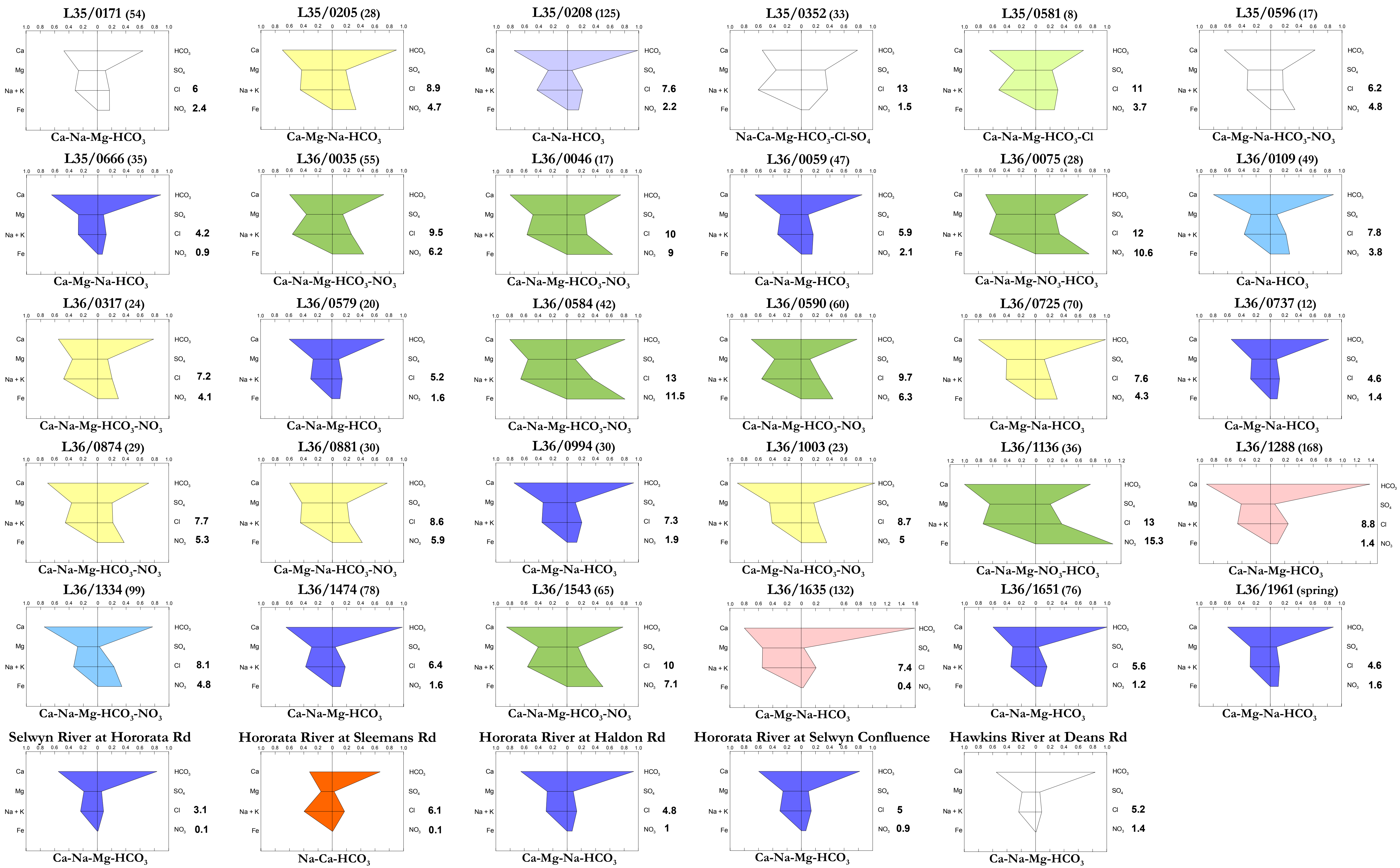
5.6.4 Determination of groundwater recharge sources

5.6.4.1 Use of Stiff plots

A useful method for displaying water chemistry results so that different groundwater recharge sources can be easily identified is the Stiff plot (Stiff, 1951). The Stiff plot utilises four parallel horizontal axes which extend on each side from a vertical zero axis. Cations are plotted on the left horizontal axes and anions on the right horizontal axes as pairs in units of milliequivalents per litre. Typical cation-anion pairs are: Ca – HCO_3, Mg –SO_4, Na + K – Cl, and Fe –CO_3. For this study the Fe – CO_3 axis was replaced by Fe – NO_3 because of the potential for NO_3 to distinguish between rainfall and river recharged groundwater. When the points of the plot are connected a distinctive polygonal pattern is produced. It is then a case of comparing patterns to identify waters of similar composition (and source). The resulting Stiff plots for the wells, spring and rivers sampled during this study are shown in Figure 5.14 and in plan view in Figure 5.15. Chloride and nitrate-nitrogen (in mg/L) and $\delta^{18}O$ values are also shown in these plots.

Figure 5.14 shows that groundwater can be separated into a number of groups based on the similarity of the Stiff patterns. Each group is represented by a particular colour (Table 5.7). River samples were included so that groundwater could be directly compared to the river pattern.

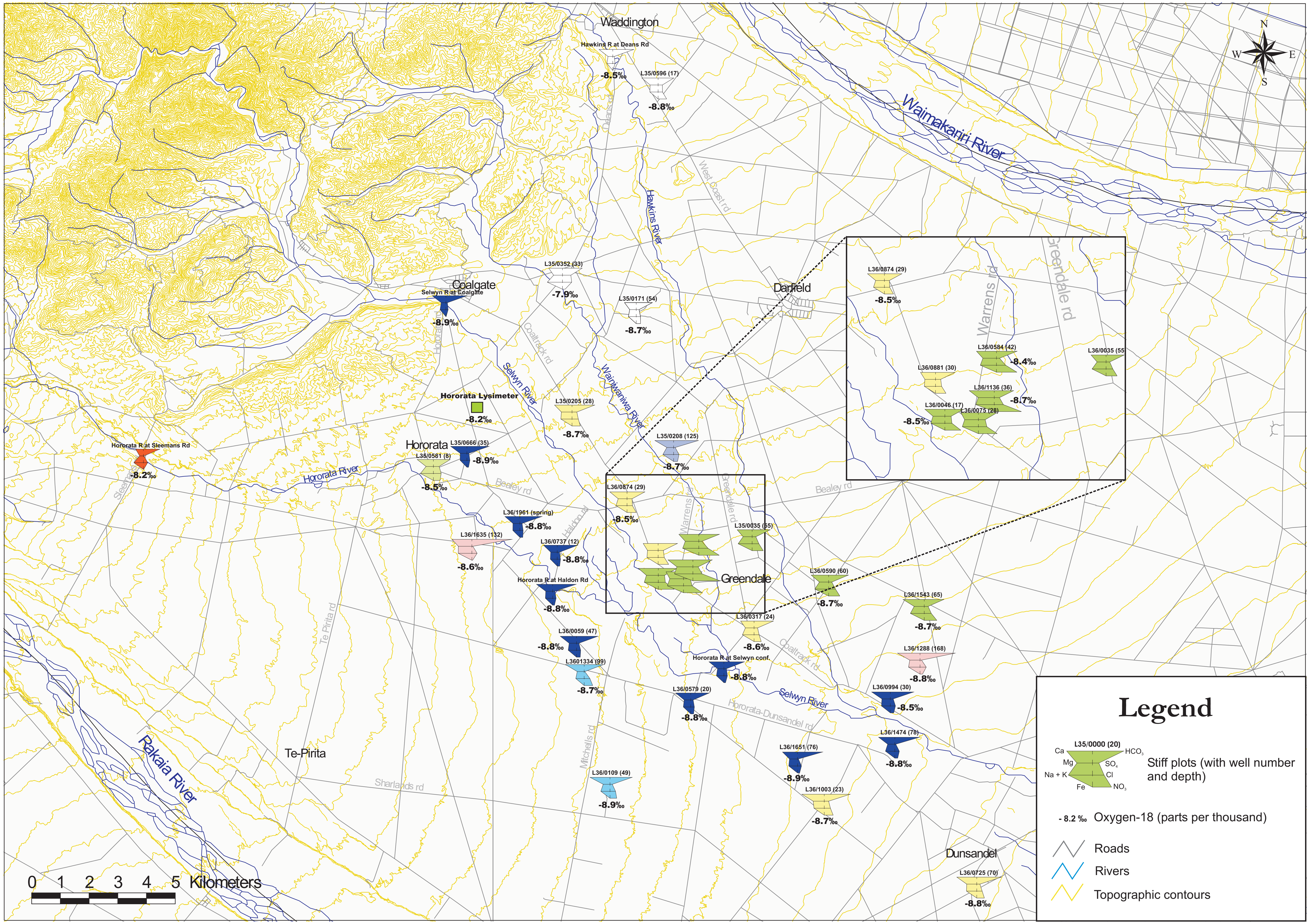
Figure 5.14. Stiff plots for sampled wells, spring and river localities.



Notes

* Chloride and nitrate-nitrogen concentrations (in mg/L) are shown next to chloride and nitrate axis respectively
* Hydrochemical facies determined by 'equivalents' technique (section 5.6) are shown at bottom of stiff plots.
* For description of stiff plot patterns see section 5.7.3 and table 5.7.

Figure 5.15. Plan view showing distribution and stiff plot patterns of sampled wells, spring and river localities.



Samples thought to have no possible influence from the Selwyn or Hororata rivers were left unshaded and do not necessarily represent the same source.

Stiff plot Colour	Well/spring number	Recharge Source
Dark blue	L35/0666, L36/0059, L36/0579, L36/0737, L36/0994, L36/1474, L36/1651, L36/1961	Dominantly Selwyn river
Light blue	L36/0109, L36/1334	Selwyn River and/or rainfall
Purple	L35/0208	Rainfall and/or Selwyn/Waianiwaniwa river
Dark Green	L36/0035, L36/0046, L36/0075, L36/0584, L36/0590, L36/1136, L36/1543	Dominantly rainfall
Light Green	L35/0581	Rainfall and/or foothills runoff
Yellow	L35/0205, L36/0317, L36/0725, L36/0881, L36/0874, L36/1003	Dominantly rainfall with Selwyn River influence
Pink	L36/1288, L36/1635	Uncertain
No colour	L35/0171, L35/0352, L35/0596	Various (see text)

Table 5.7 Differentiation of wells into groups and likely recharge sources based on similarities of Stiff plot patterns.

5.6.4.2 Dark blue patterns (river recharge)

All dark blue patterns (L35/0666, L36/0059, L36/0579, L36/0737, L36/0994, L36/1474, L36/1651, L36/1961) have low ionic concentrations (narrow width) including low nitrates (0.9 to 2.1 mg/L NO_3-N) and low chloride (4.2 to 7.3 mg/L) indicating dominantly river recharged water (Figures 5.14 and 5.15). The Selwyn River at Hororata Road has the lowest ionic and nitrate concentrations, and a $\delta^{18}O$ value of -8.9‰ as it emerges from the foothills. The $\delta^{18}O$ values for all the dark blue patterns (with the exception of L36/0994) are between -8.8‰ and -8.9‰ which is close to that of the Selwyn River at Hororata Road.

L35/0666, L36/0737 and L36/1961 all have identical shapes which are similar to that of the Selwyn River at Hororata Road, but with slightly greater ion concentrations (thicker shape). The proximity of these three samples to the Selwyn River indicated they are sourced directly from the Selwyn River. This is also evidenced from river gaugings and water levels: gaugings indicate significant losses from the Selwyn River to shallow groundwater in this area; and water levels in the vicinity of L35/0666 and L36/0737 correlate strongly with flow in the Selwyn River at Whitecliffs. The slight increase in ionic concentrations of these samples (including an increase in chloride and nitrate) is probably due to longer residence times and/or a small added rainfall component. The slightly less negative $\delta^{18}O$ values for L36/1961 and L36/0737 may also reflect an added rainfall component with distance from the source.

The pattern for the Hororata River at Sleemans Road is different from that of the Hororata River at Haldon Road and the Selwyn confluence. Similarly, the $\delta^{18}O$ value (-8.2‰) is more positive. The similarity of the patterns and $\delta^{18}O$ values for the Hororata River at Haldon Road and the Selwyn confluence to the groundwater and spring between the Selwyn and Hororata rivers (L35/0666, L36/0737 and L36/1961) indicates that the main input into the Hororata River from Haldon Road downwards is Selwyn River derived springflow (Figure 5.15). This is also inferred from river gaugings. Discharge of spring-fed streams into the Hororata River, are shown in figure 3.10 (section 3.3.3). The difference in pattern and $\delta^{18}O$ between the Hororata River at Sleemans Road and the Selwyn River at Hororata Road probably reflects a difference in source area altitude and rock types within the Hororata and Selwyn river catchments. The higher chloride and less negative $\delta^{18}O$ in the Hororata River at Sleemans Road, suggests the Hororata River is sourced from lower altitude rainfall than the Selwyn River.

The similarity of the $\delta^{18}O$ values and the patterns of L36/0579 and L36/0059 to samples L35/0666, L36/0737 and L36/1961 (described above) suggest aquifer 1 and 2 immediately south of the Hororata River are recharged from Selwyn River derived water (Figure 5.15). This is also indicated from water levels: water levels in L36/0579 correlate strongly with flow in the Hororata River; L36/0059 shows small variations in water levels reflecting a more constant recharge source (river) unlike that expected for rainfall recharge. Additionally, the slightly higher chloride concentrations in these two wells suggest an increasing rainfall component with distance from the source (Selwyn River). Aquifer 1 is probably recharged from losses from the Hororata River whereas aquifer 2 may also be recharged laterally from groundwater underpassing the Hororata River.

L36/0994 has the greatest ionic concentrations, including highest chloride, of the dark blue pattern (river recharge) shallow groundwater and is also the furthest away from the foothills (Figure 5.15). The increase in ionic concentrations maybe the result of greater residence times but the higher chloride (7.3 mg/L) also suggests a significant component of direct or higher altitude rainfall recharge. The $\delta^{18}O$ value for this well is -8.5‰ and is more positive than the other blue patterns. For the majority of the year the Selwyn River goes dry at least 2 km upstream of this well but may flow past it for a few months of the year during “high flow” events.[1] During these "high flow" events a major component of the Selwyn River is surface runoff which would reduce the $\delta^{18}O$ value of the river (i.e. more positive than normal). Therefore, the $\delta^{18}O$ and chloride values for this well probably reflect a mixture of rainfall and recharge from the Selwyn River during high flows.

The $\delta^{18}O$ and patterns of L36/1474 and L36/1651, located within the second aquifer on the south side of the Selwyn River, indicate a significant amount of groundwater in this area is derived from the Selwyn River (figure 5.15). The chloride concentrations are similar to that of L36/0059 and imply an increasing rainfall component with distance and depth from the Selwyn River. These two wells have slightly higher concentrations of sodium and bicarbonate than the other dark blue patterns which probably indicates greater residence times reflecting the greater depth of these wells.

5.6.4.3 Dark Green patterns (rainfall recharge)

All wells with dark green patterns (L36/0035, L36/0046, L36/0075, L36/0584, L36/0590, L36/1136 and L36/1543) are characterized by greater ionic concentrations (thicker shape) including higher chloride (9.5 to 13 mg/L) and nitrate concentrations (6.2 to 15.3 mg/L NO_3-N) indicating dominantly rainfall recharge. Variations in ions between wells probably reflect a difference in residence times and/or contamination of the groundwater. The $\delta^{18}O$ values are variable (from -8.4‰ to -8.7‰) but are lower than those of the blue patterns (river recharge).

All of the dark green pattern wells are situated on the north side of the Selwyn River (Figure 5.15), which suggests that most groundwater within this region is sourced from rainfall.

5.6.4.4 Light blue patterns

The two light blue patterns (L36/0109 and L36/1334) look similar to the dark blue (river recharge) patterns but have chloride (7.8 to 8.1 mg/L) and nitrate concentrations (3.8 to 4.8 mg/L NO_3-N) in-between those of the river-recharged and rainfall-recharged (dark green) wells (Figures 5.14 and 5.15). Piezometric contours suggest flow to these wells is from the direction of Selwyn River recharged areas i.e. from the direction of L36/0059. It is likely that these wells receive some Selwyn River recharge with the higher chloride and nitrate concentrations suggesting an increasing dominance of rainfall with distance (southwards) and depth from the river. The more positive $\delta^{18}O$ value (-8.7‰) for L36/1334 also indicates an increasing rainfall

[1] High flow events are events in which the Selwyn River flows over most of its length from the foothills to Dunsandel.

component for this well. The low sulphide concentration and greater depth of well L36/1334 suggests sulphate reduction and longer residence times.

5.6.4.5 Yellow patterns

The yellow patterns (L35/0205, L36/0317, L36/0725, L36/0881, L36/0874 and L36/1003) look similar to the dark green (rainfall recharge) patterns but with slightly lower chloride (7.2 to 8.9 mg/L), nitrate (4.1 to 5.9 mg/L NO_3-N) and sodium concentrations (Figure 5.14). Wells L35/0205, L36/0317, L36/0881, L36/0874 and to a lesser extent L36/1003 are situated close to the Selwyn River but in areas where the Selwyn River is dry for most of the year (Figure 5.15). These wells are therefore probably dominantly rainfall recharged but perhaps receive intermittent recharge from the Selwyn River during high flows. Water levels also suggest a possible seasonal influence from the Selwyn River to these wells. $\delta^{18}O$ values for these wells varied from -8.5‰ to -8.7‰.

L36/0317 is also located between the Hawkins and Waianiwaniwa rivers (Figure 5.15). Although these rivers rarely flow into the Selwyn River when they do the shallow aquifer is significantly affected. L36/0317 may therefore also receive an occasional but significant recharge component from the Hawkins/Waianiwaniwa rivers when they flow into the Selwyn River.

L36/0725 is located within the second aquifer and is likely to be the downstream continuation of aquifer 2 from wells L36/1651 and L36/1474 which show dominantly river recharge. This well is therefore likely to be a mixture of river and rainfall recharge. $\delta^{18}O$ for this well (-8.8‰) is similar to that of values expected for Selwyn River recharged areas.

5.6.4.6 Pink patterns

The two pink patterns (L36/1288 and L36/1635) are quite distinct from any others. The pattern of high HCO_3 and low SO_4 is indicative of long residence times and evolved New Zealand groundwater on the Chebatorev sequence (section 5.4.5). The old age of these wells is confirmed by groundwater isotopes (Chapter 6). The distinct patterns make it difficult to assign a recharge source and illustrate the difficulties of determining recharge sources for old evolved groundwater from chemistry. The chloride concentrations (7.4 to 8.8 mg/L), if not significantly changed with residence time, would suggest a dominantly rainfall recharged source for these 2 wells. The $\delta^{18}O$ value for L36/1635 (-8.6‰) also suggests a rainfall source for this well. However, the more negative $\delta^{18}O$ value (-8.8‰) for L36/1288, together with piezometric contours, suggest a possible influence from the Selwyn River area to aquifer 3 in this well. The low nitrate values for these two wells may reflect a reduction in oxidation potential with depth but may also reflect less intensive farming practices during the time of recharge.

5.6.4.7 Purple pattern

The purple pattern (L35/0208) looks similar to the dark blue (river recharge) patterns but with sodium and chloride concentrations more similar to the yellow patterns (dominantly rainfall with Selwyn River component) (Figure 5.14). The low sulphate and depth of this well suggests long groundwater residence times which creates uncertainty in assigning a source. The location, depth and $\delta^{18}O$ value for this well (-8.7‰) suggest a dominantly rainfall recharged source but with possible a small influence from the Selwyn and/or Waianiwaniwa rivers.

5.6.4.8 Light green pattern

The light green well (L35/0581) has a pattern very similar to the dark green (rainfall recharge) wells but with less nitrates. The high chloride value for this well (11 mg/L), together with its proximity to the foothills, suggests it is recharged dominantly from rainfall and/or foothills runoff. The low nitrate concentration (3.7 mg/L NO_3-N) probably reflects the close proximity to the foothills with little farming activities upgradient. The $\delta^{18}O$ value (-8.5‰) also indicates a rainfall recharged source for this well.

5.6.4.9 Non-coloured patterns

The non-coloured patterns were considered to have no possible connection with the Hororata or Selwyn rivers.

The Hawkins River at Deans Road has a pattern almost identical to that of the Selwyn River at Hororata Road. These similarities probably reflect similar catchment altitudes and/or source rock characteristics (mostly greywacke) between the Selwyn and Hawkins rivers. However, the lower $\delta^{18}O$ value for the Hawkins River (-8.5‰) than the Selwyn (-8.9‰) may indicate a slightly lower altitude catchment area for the Hawkins River.

L35/0352 has a pattern similar to the dark green (rainfall recharge) wells but with very low nitrate (1.5 mg/L) and higher sulphate concentrations. The high chloride (13 mg/L) in this well infers a dominantly rainfall recharge source with the low nitrates reflecting the close proximity to the foothills and little farming upgradient. However, the proximity of this well to the

Waianiwaniwa River suggests it may also receive periodic river recharge from the Waianiwaniwa River when it flows from the foothills. The chemistry of this well is likely to change throughout the year reflecting flow events in the Waianiwaniwa River.

L35/0596 and L35/0171 have fairly similar patterns. The well locations and chloride concentrations probably reflect a mixture of recharge from the Hawkins River and rainfall.

5.7 Discussion

The average $\delta^{18}O$ value for the Selwyn River between September 1977 and June 1978 was – 8.97‰, but with variations from -8.2‰ to -9.5‰ (Figure 5.13 and Appendix 5.2). A more reliable value for average $\delta^{18}O$ for the Selwyn River can be obtained from wells recharged from the river because seasonal and longer-term trends are smoothed out by dispersion and mixing of water within the aquifer. Wells shown to be recharged from the Selwyn River from water chemistry (L35/0666, L36/0059, L36/0579, L36/0737, L36/0994, L36/1474 and L36/1651) indicate that the average $\delta^{18}O$ value for the Selwyn River is between –8.8‰ and –8.9‰. Ages obtained for four of these wells (L35/0666, 37 years; L36/0059, 33 years; L36/0579, 26 years; and L36/1651, 40 years) give confidence in these results (Chapter 6). This value is in contrast to the average $\delta^{18}O$ value of –8.7‰ suggested by Stewart et al (2002). The $\delta^{18}O$ value of –8.7‰ was obtained mostly from wells located on the northern side of the Selwyn River near Greendale (Mike Stewart, Institute of Geological and Nuclear Sciences, pers.comm., 2005). However, groundwater chemistry shows these wells are dominantly rainfall-recharged with little influence from the Selwyn River.

The chloride concentrations of all the dominantly rainfall recharged wells (9.5 to 13 mg/L) are close to the minimum chloride values of 10 to 20 mg/L expected for rainfall recharged groundwater in the Christchurch-West Melton area (Hayward, 2002). These differences agree with the assumption of Stewart et al (2002) that chloride concentrations in rainfall recharged groundwater decrease inland with distance from the coast but are lower than the average rainfall value (16.40 mg/L) for the Hororata Lysimeter. Similarly, $\delta^{18}O$ values for rainfall recharge (- 8.4‰ to –8.7‰) are more negative than values for the Hororata Lysimeter (-8.2‰).

The lower chloride and more negative $\delta^{18}O$ values for rainfall recharge than expected from the Hororata Lysimeter would suggest that direct rainfall recharge is not dominant for any of the wells. However, the Hororata Lysimeter has just five years of data and measures rainfall recharge for only 80cm of soil depth. The distribution of $\delta^{18}O$ with depth in the unsaturated zone is complex and may differ from that of the $\delta^{18}O$ value at the surface (Taylor et al, 1989). The unsaturated zone is at least 10 metres thick in areas overlying rainfall recharged groundwater within the field area. Processes within the unsaturated zone may therefore be partially responsible for differences between $\delta^{18}O$ and chloride values between the Hororata Lysimeter and rainfall recharged areas. Fluctuations in $\delta^{18}O$ are essentially absent below the water table (Allison et al, 1984). It is also possible that rainfall recharged wells within aquifers 1 and 2 also receive some slow and/or intermittent Selwyn River recharge. This is tentatively indicated by piezometric contours and may account for the slightly more negative $\delta^{18}O$ and lower chloride values for these wells. Similarly, the high levels of contamination (nitrates) in rainfall recharged wells (dark green patterns) may mask any evidence of a slight Selwyn River influence.

Overall, more data needs to be collected from the Hororata Lysimeter to give greater confidence in the results at that site. At the moment the best estimate for an average $\delta^{18}O$ value for rainfall recharge is likely to be reflected in deeper rainfall recharge wells (L36/0590 and L36/1543) from which seasonal and longer-term variations are likely to have been smoothed out. Given the possibility that some Selwyn River derived water may be recharging to these wells a minimum average $\delta^{18}O$ value of -8.7‰ for rainfall recharge is suggested.

The closeness in $\delta^{18}O$ values between rainfall and river recharge mean $\delta^{18}O$ is not a particularly good indicator of recharge source within the field area and should be supplemented by water chemistry. The uncertainty in identifying recharge sources is reflected in the large range of $\delta^{18}O$ values (-8.1‰ to -9.2‰) in wells previously sampled in 1976 in aquifers 1 and 2 within the Greendale area (Figure 5.12). The $\delta^{18}O$ values in all but one of these wells is below the rainfall recharge estimate of -8.7‰ and may indicate a long term negative shift in $\delta^{18}O$ of rainfall recharge over time in this area.

Wilson (1973) suggested that groundwater is likely to stay confined to the river (fan) deposits in which they were derived. With this in mind the presence of dominantly rainfall recharged groundwater on the northern side of the Selwyn River around the Warrens and Coaltrack Road intersection imply that the river did not flow north to this area from its current position at depth i.e. gravel deposits in aquifer 2 north of the present location of the Selwyn River are not derived from the Selwyn River but more likely from the Waianiwaniwa River. Wells L35/0205 and L36/0874 are located in Selwyn River derived Burnham gravels on the north side of the river but show only a small influence from the river. This is probably due to the fact that the Selwyn River runs dry for the majority of the year shortly after its emergence from the foothills but borelogs show extensive claybound gravel units to the north of the present location of the river which may be acting as a barrier to flow in that direction. Conversely, the dominance of river recharged groundwater on the southern side of the river suggests that the river used to flow extensively to the south of its present location.

Piezometric contours imply that the Waimakariri and Rakaia rivers have little or no input to the groundwater resources within the field area.

Piper diagrams and non-graphical equivalents methods (section 5.6) are less useful in distinguishing recharge sources in aquifers of similar lithology. Both methods plot concentrations as percentages and as such waters of very different composition (and recharge source) can belong to the same hydrochemical facies if the relative abundance of the ions is similar. This is illustrated in figure 5.14 where hydrochemical facies, as determined by the equivalents method, show no relationship to the different recharge sources (Stiff plot patterns). These methods are more useful in distinguishing waters on a regional scale from aquifers of distinctly different chemical composition.

5.8 Chapter Summary

Water chemistry from selected wells, springs and rivers showed that some samples transgressed the 2000 New Zealand Drinking Water Standards for pH and nitrate-nitrogen. An area of nitrate-nitrogen elevated above half of the maximum acceptable value was identified in the Greendale area and is likely to be caused by agricultural activities upgradient of the source area.

Two deeper wells (L36/1288, 168m; L36/1635, 132m) showed high bicarbonate and low sulphate concentrations indicative of evolution along the Chebatorev sequence and old groundwater ages. All other wells showed little evidence for evolution along the Chebatorev sequence.

Piper diagrams showed that all water within the field area could be classified as either calcium-bicarbonate or no dominant cation-bicarbonate waters. No obvious trends between position on piper diagram and well depth or location could be identified.

Stiff plots showed that groundwater could be divided into a number of groups based on the similarity of the patterns. These Stiff plot patterns combined with chloride, nitrate-nitrogen (mg/L) and $\delta^{18}O$ concentrations enabled likely groundwater recharge sources to be identified.

Dominantly river-recharged groundwater was identified extensively in aquifers 1 and 2 on the south of the present day Selwyn River. Dominantly rainfall-recharged groundwater was identified in aquifers 1 and 2 on the north side of the Selwyn River in the Greendale area. Other wells showed varying degrees of river and rainfall influence.

An average $\delta^{18}O$ value of –8.8‰ to –8.9‰ was estimated for groundwater recharged dominantly from the Selwyn River. In contrast, rainfall recharge within the field area was estimated to have a minimum average $\delta^{18}O$ value of –8.7‰. The closeness in $\delta^{18}O$ values between river and rainfall recharge in the area imply that $\delta^{18}O$ by itself is not a good indicator of recharge source within the field area but should be complimented by water chemistry.

Chapter Six

Groundwater Ages

6.1 Introduction

A number of wells were sampled for groundwater age-dating tracers. The main objectives of the tracer sampling programme were:

- To determine the age of the groundwater through the use of the age dating tracers tritium, CFCs and SF_6
- To identify and discuss any differences and/or trends in groundwater ages calculated from the different techniques
- Discuss the implications of groundwater ages on recharge sources and groundwater management

6.2 Age dating methods

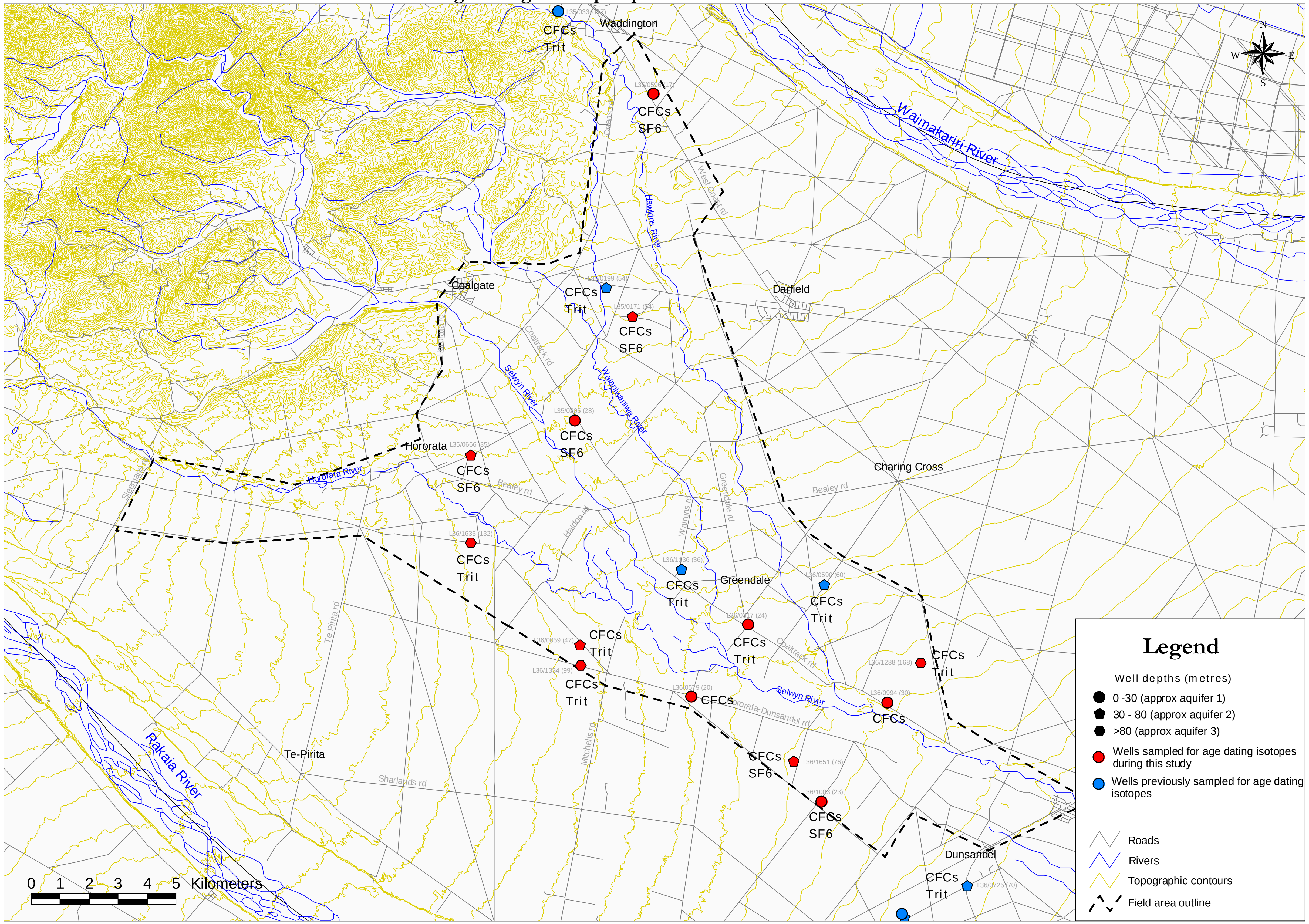
Determining the age of groundwater is important because it can provide valuable information on the groundwater resources such as flow rates and paths, sustainable yields and vulnerability of the aquifers to contamination. There are a number of techniques used for dating groundwater including tritium, CFCs and SF_6.

Tritium and CFC samples had been previously analysed for only a selected number of wells within the field area prior to this study (Figure 6.1). No wells had been previously sampled for SF_6 and this study was one of the first applications of this method within New Zealand.

6.2.1 Tritium

Tritium is an unstable isotope with a radioactive half-life of 12.3 years. Tritium occurs naturally in the atmosphere (and thus rainfall) in very small but constant quantities. Up until the 1960s tritium concentrations were at background levels. Concentrations then increased substantially during the 1960s and 1970s due to atmospheric nuclear weapons testing, before gradually decreasing to background levels again from about 1985. The variation in tritium concentrations

Figure 6.1. Location of wells sampled for age dating isotopes within the field area (includes samples collected during this study and previously sampled). note: the different age dating techniques performed on each well are shown next to the well



in rainfall for Kaitoke, New Zealand with time is shown in figure 6.1. On infiltration into the ground the tritium concentration of rainfall becomes separated from that of the atmosphere, and apart from radioactive decay no underground processes affect the tritium concentration (Stewart and Morgenstern, 2001). The residence times of rainfall recharge can thus be calculated based on the radioactive decay rate of tritium and comparison with concentrations in the atmosphere over time. Tritium ages for groundwater within the Canterbury Plains are calculated using the Kaitoke rainfall data (Figure 6.2), but have to be multiplied by a factor of 1.25 to adjust for latitude and longitude differences between the two locations (Stewart et al, 2002).

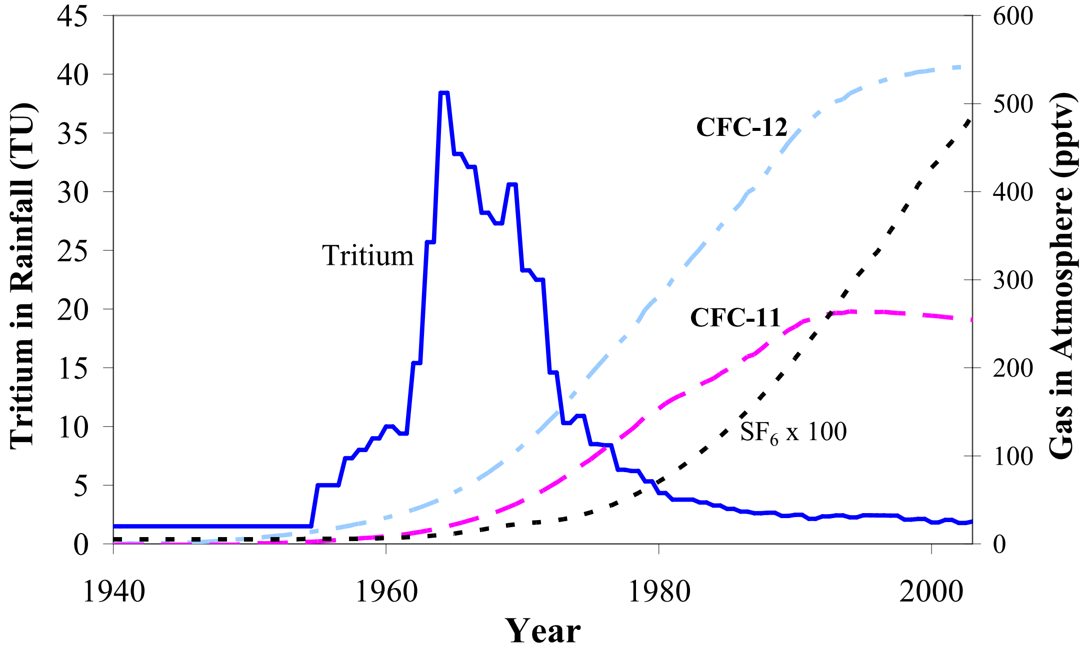


Figure 6.2 Tritium concentrations in rainfall at Kaitoke, New Zealand, and CFC and SF_6 concentrations in the Southern Hemisphere atmosphere with time (from Stewart, 2005).

Interpretation of groundwater residence times using tritium can be difficult. Often three possible ages can be inferred from the one tritium concentration because of the changes in concentration with time (Stewart and Morgenstern, 2001).

Tritium has been successfully used to age date groundwater in the Canterbury plains since the 1960s.

6.2.2 Chlorofluorocarbons (CFCs) and sulphur hexafluoride (SF_6)

Chlorofluorocarbons (CFCs) are a group of entirely manmade compounds containing chlorine, fluorine and carbon. The production of CFCs began in the 1930s for the purpose of refrigeration. Since then they have also been used industrially for air conditioning, blowing agents in foam manufacture, and pressurizing aerosol cans (Stewart and Fox, 1997). Concentrations in the atmosphere have gradually increased from zero in the 1940s to present values of several parts per trillion (pptv), reflecting their increasing industrial use (Figure 6.2). The main CFCs used in age dating are CFC-11, CFC-12 and CFC-13. CFC-11 is not effective for determining groundwater ages from about 1990 because concentrations have remained almost constant from this time. Similarly, the rate of increase in CFC-12 concentrations have declined since 1990, which means CFC-12 is less accurate for age dating waters younger than this time. CFCs were first used to date groundwater within the Canterbury plains in 1997 (Stewart and Fox, 1997).

Sulphur hexafluoride (SF_6) is a manmade gas primarily used in the electric power industry as insulation. SF6 concentrations have slowly increased in the atmosphere from about the 1970s, but unlike CFCs their concentration is still accelerating (Figure 6.2). This makes SF6 particular useful in dating younger waters. The SF6 technique has only recently been applied to groundwaters in New Zealand for age dating purposes (van der Raaij, 2003).

Water recharging to groundwater aquifers contain small amounts of CFCs and SF_6 in solution reflecting their concentrations in the atmosphere at the time of recharge which allows the age of the groundwater to be determined.

6.3 Tracer Sampling Programme

A total of 13 wells were sampled for age dating tracers during February 2005. All but two of those samples were analysed by more than one dating technique. The sampled wells and techniques are shown in figure 6.1 and table 6.1.

Well no	Well depth (m)	Groundwater tracer sampling technique[1]			
		Tritium	CFC-11	CFC-12	SF_6
L35/0171	54		√	√	√
L35/0205	28		√	√	√
L35/0596	17		√	√	√
L35/0666	35		√	√	√
L36/0059	47	√	√	√	
L36/0317	24	√	√	√	
L36/0579	20		√	√	
L36/0994	30		√	√	
L36/1003	23		√	√	√
L36/1228	168	√	√	√	
L36/1334	99	√	√	√	
L36/1635	132	√	√	√	
L36/1651	76		√	√	√

Table 6.1 Sampled wells and groundwater dating techniques.
[1] √ means well sampled for that technique.

Appropriate measures were taken to ensure that the CFC and SF_6 samples did not come into contact with the atmosphere to avoid possible contamination. All isotopes were analysed by the Tritium and Water Dating Laboratory at the Institute of Geological and Nuclear Sciences (GNS), Wellington, New Zealand.

6.4 Age data analysis

6.4.1 Interpretation basics

Tritium ages were calculated from 20% and 50% exponential piston flow (mixing) models; CFCs ages from a piston flow model and a 50% mixing model; and SF_6 ages from a 50% mixing model. The piston flow model assumes all of the water in the sample has the same age i.e. groundwater travels as a “front” with no dispersion and mixing of water within the aquifer. The exponential piston flow (mixing) model assumes that water travels through many different flow paths within the aquifer (i.e. there is a distribution of different ages within the different flow paths in the aquifer), and that these waters (ages) are mixed at the sample outlet (i.e. the pumped well). The 20% and 50% mixing models assume piston flow with 20% and 50% mixing respectively. A more detailed explanation of mixing models can be found in Stewart et al (2002) and Stewart (2005).

Well no	Well depth (m)	Mean age (in years) based on mixing model shown							Recommended mean age (years)
		Tritium		CFC-11	CFC-12	CFC-11	CFC-12	SF_6	
		20%	50%	PF	PF	50%	50%	50%	
L35/0171	54			24	16	25	15	3	25
L35/0205	28			35	24	48	26	8	48
L35/0596	17			18	4	15	0-3	0	<15
L35/0666	35			30	20	37	21	6	37
L36/0059	47	1,29,46	1,~39	29	17	33	17		33
L36/0317	24	1,30,46	1, ~39	25	C	27	C		27
L36/0579	20			25	11	26	9		26
L36/0994	30			18	C	17	C		<17
L36/1003	23			C	C	C	C	1	?
L36/1288	168	61	90	49	48	78	71		90
L36/1334	99	51	70	41	35	59	46		70
L36/1635	132	>70	>95	51	55	82	85		>95
L36/1651	76			32	24	40	26	8	40

Table 6.2 Age interpretation for tritium, CFC and SF_6 using piston flow and 20% and 50% exponential mixing models. 'C'means the sample is contaminated.

Table 6.2 shows that calculated ages are strongly dependant on the choice of mixing model, but with different samples exhibiting varying degrees of sensitivity. In most samples, the calculated ages for CFCs were younger for the piston flow model than the 50% mixing model. Conversely, calculated tritium ages were significantly older for the 50% mixing model than the 20% model. The calculated ages for the different dating techniques were consistently different with tritium giving the oldest ages followed by CFC-11 then CFC-12 and SF_6 giving the youngest age.

CFC-11 ages for wells L36/0317, L36/0994 and L36/1003 and CFC-12 for L36/1003 could not be calculated because of contamination. Contamination of CFCs result in CFC concentrations that are higher than would normally be expected from solution from the atmosphere. The likely source for the contamination is agricultural chemicals, which may indicate a dominantly rainfall recharge source for these wells.

6.5 Groundwater ages

Results for tritium, CFC and SF_6 sampling are given in Table 6.2 and the raw data in Appendix 6.1. A recommended age was assigned to each sample by Stewart (2005) (Table 6.2). This age in all cases was based on either the tritium or CFC-11 age for the 50% mixing models. The 50% mixing model is probably the most representative of groundwater within the Selwyn area (Stewart, 2005). These recommended ages, together with ages calculated from previous samples, are shown in plan view in figure 6.3. An age for well L36/1003 could not be estimated because both CFC samples were contaminated.

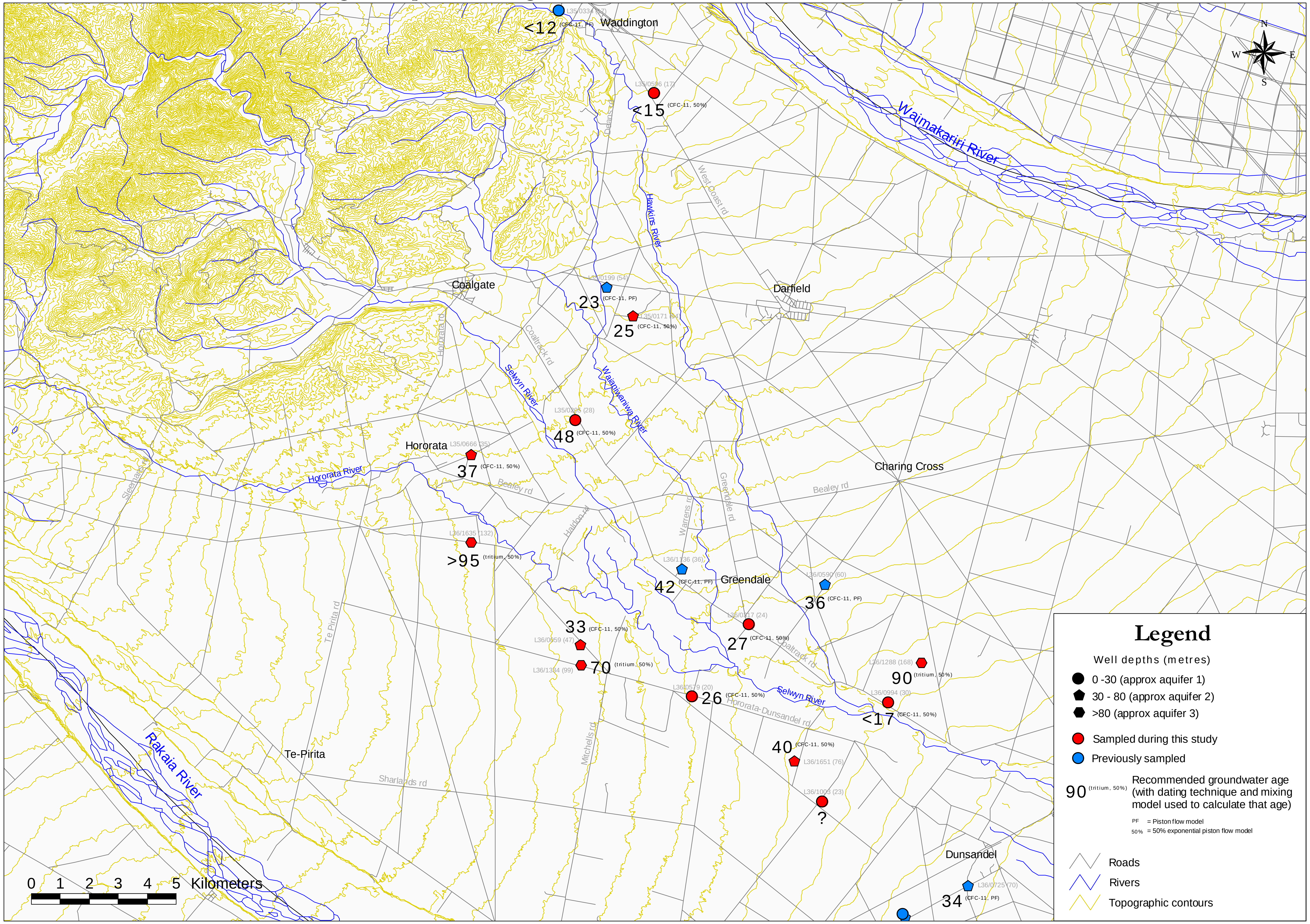
Groundwater ages for wells L35/0596 and L35/0171 were <15 years and 25 years respectively. These ages are very similar to the ages previously obtained for nearby wells L35/0334 and L35/0199, which are located at similar depths, and gives confidence in the results. The young ages suggest reasonably quick penetration of water into aquifers 1 and 2 which agree with a mixed Hawkins River/rainfall recharge source suggested by water chemistry.

The age of groundwater for well L35/0205 (48 years) is reasonably old considering the well is only 28m deep. Borelogs from surrounding wells indicate reasonable extensive claybound gravels between 4 and 12 metres below the surface in that area. These claybound gravels may be acting as a relatively impermeable barrier to groundwater flow resulting in extremely slow seepage (and thus old groundwater) to this locality. The older age may also indicate upwelling of older, deeper groundwater to the shallow aquifer. The age of this well suggests a dominantly rainfall recharge source which agrees with the water chemistry results.

The recommended age for groundwater within well L35/0666 is 37 years. Water chemistry, $\delta^{18}O$, river gaugings and piezometric contours suggest that this well is recharged dominantly from the Selwyn River which is approximately 5 km away. The reasonably old age, together with the short travel distance from the source, suggests slow seepage of groundwater through the aquifer. However, transmissivity calculated from a pump test on well L35/0751, at a similar depth and location to L35/0666, was high (12,000 m^2/day) implying reasonable rapid groundwater flow. This high transmissivity combined with the old groundwater age may indicate upwelling of older groundwater to this area. Borelogs from nearby wells show persistent claybound gravels from approximately 15 to 25 metres and greater than 40 metres below the ground surface which may be acting as relatively impermeable barriers to flow. The age suggests that the reasonably rapid response of groundwater levels to flow within the Selwyn River in this area can be attributed to the push out of older stored water by a pressure effect controlled by flow within the Selwyn River rather than from direct recharge of younger river water.

The recommended ages for groundwater within wells L36/0059 and L36/0579 are 33 and 26 years respectively. Water chemistry, $\delta^{18}O$ and piezometric contours suggest these wells are derived from surface losses from the Hororata River, which is sourced from Selwyn River

Figure 6.3. Recommended groundwater ages for wells sampled during this study and previously sampled wells.
(Dating technique and mixing model used to calculate the recommeded age are also shown)



derived spring-fed streams from the direction of well L35/0666. This evidence would suggest that the ages for these two wells should be older than L35/0666, because they are essentially derived from surface losses from the Hororata River, which gains it flow from spring-fed streams from groundwater coming from the direction of L35/0666, yet they are younger. The younger ages may result from the increased addition of younger rainfall between the Selwyn and Hororata rivers. However, the likely explanation for the younger ages is that the CFCs have been reset or partially reset to values of the atmosphere whilst in the Hororata River i.e. the CFCs are re-equilibrated with the atmosphere on emergence from the ground. These ages therefore represent the recharge time of groundwater derived from losses from the Hororata River, rather than the time of recharge from the original source (Selwyn River). Given that the CFCs may only have been partially reset the ages, for these two wells are likely to represent the maximum time taken for groundwater to percolate to the aquifer 1 and/or 2 from the time of surface losses from the Hororata River. The slightly older age of L36/0059 probably reflects the depth of this well but may also indicate a small component of groundwater recharge underpassing the Hororata River.

Water chemistry showed that well L36/1651 was also recharged from dominantly Selwyn River derived water. It is likely that the 40 year old age for groundwater in this well simply reflects the greater depth and distance from the source than wells L36/0059 and L36/0579.

Wells L36/1136 and L36/0590, sampled prior to this study, have recommended groundwater ages of 42 and 36 years respectively. These ages were calculated by a piston flow model and are probably slightly younger than would be obtained from a more realistic 50% mixing model. Nonetheless, the older ages indicate slow seepage and a dominantly rainfall recharge source which is also indicated by water chemistry.

Wells L36/0317 and L36/0994 have recommended groundwater ages of 27 and <17 years respectively suggesting reasonably rapid recharge to these areas. The younger ages for L36/0317 and L36/0994 compared to L36/1136 and L36/0590 may reflect the shallower depth of the wells, but may also indicate a component of more rapid recharge from the Selwyn River during high flow events as indicated by water chemistry.

Very old groundwater ages of 70, >95 and 90 years were calculated for wells L36/1334, L36/1635 and L36/1288 respectively. The older ages reflect the greater depth of the wells which all draw water from aquifer 3. A pump test performed on well L36/1226, which is at a similar depth and location to L36/1635, indicate low transmissivities (900 m^2/day) for aquifer 3 in that area. The low transmissivities and old groundwater age necessitate the need for careful management of the deeper groundwater resources immediately south of Hororata township.

In general, wells shown to be dominantly river recharged by water chemistry and $\delta^{18}O$ had slightly younger ages than those for dominantly rainfall recharge wells.

6.5.1 Groundwater age discussion

The pattern of tritium giving the oldest groundwater age followed by CFC-11 then CFC-12 and SF6 giving the youngest age for most wells could be explained by the natural process of penetration of the different tracers through the unsaturated zone. Although not well understood the behaviour of the different tracers within the unsaturated zone is likely to be different (Stewart, 2005):

- Tritium is unlikely to be affected by unsaturated zone processes and will therefore travel at a similar rate to that of water.
- CFCs and SF_6 can travel more quickly than water through the unsaturated zone because they mainly occupy vapour-dominated pores.
    - SF_6 is the most volatile of the chemicals, and the least soluble in water, and is therefore likely to penetrate much more easily through the unsaturated zone.
    - CFC-11 is less volatile and is more susceptible to degradation and/or absorption processes in the unsaturated zone resulting in less easy penetration through the unsaturated zone.
    - CFC-12 has characteristics intermediate between those of SF_6 and CFC-11.

The behaviour of these tracers would produce the pattern of ages observed with the difference in ages between each technique related to the thickness of the unsaturated zone. The groundwater age in this case would represent the cumulative time of water transport within the unsaturated zone and the aquifer. Assuming that river recharge largely bypasses the unsaturated zone this process would imply that rainfall recharge is more prominent in the field area than indicated by water chemistry.

Alternatively, the pattern of ages could be attributed to the interaction of the gases with the atmosphere during transport of the gases through surface bodies (rivers/creeks). CFC and SF_6

groundwater ages in wells L36/0579 and L36/0059 downstream of L35/0666 suggest that CFCs and SF_6 are reset or partially reset during emergence from groundwater into the Hororata River. The different methods may exhibit the same age trends within the surface body as they do in the unsaturated zone. SF_6 may completely equilibrate with the atmosphere during surface transport and be reset to zero, CFC-12 partially reset and CFC-11 then tritium showing the least equilibrium with the atmosphere which would explain the patterns of ages observed. In such a case, tritium ages would represent the time of rainfall infiltration within the catchment zones or a composite age for groundwater that has spent more than one cycle through the ground i.e. groundwater that has emerged at the surface and then recharged as groundwater again. The CFC ages, especially CFC-11, could "inherit" a considerable age from groundwater before it enters the surface body and would explain the greater than expected ages for wells L35/0666 and possibly L35/0205 but would assume long "hold-up" times for seepage of water through the Selwyn River catchment rocks. The SF_6 technique may be the most appropriate for determining the age of groundwater infiltration from the time it was recharged from surface water losses. A comparison of tritium, CFC and SF_6 ages between the Selwyn River shortly before it emerges from the foothills and nearby river recharged groundwater may shed more light on this theory. This process would imply that river recharge is more prominent in the field area than indicated by water chemistry.

It is likely that both processes play a major part in the field area with the age trends in rainfall recharged groundwater largely the result of the behaviour of the gases through the unsaturated zone and the trends in river recharged wells largely a result of the differing degree of reaction of the gases with the atmosphere on travel through surface bodies.

6.6 Chapter Summary

Calculated groundwater ages from tritium, CFCs and SF_6 were strongly dependant on the mixing model used. In general, calculated CFC ages were younger for a piston flow model than a 50% mixing model and tritium ages were older for a 50% mixing model than a 20% model.

Overall, groundwater ages were older for deeper wells and areas inferred to be dominantly rainfall recharged from water chemistry and $\delta^{18}O$. The old groundwater age for well L36/1635, together with low transmissivity values calculated for other wells at similar depths and location, imply careful management of the groundwater resources in that area.

The groundwater ages for wells L35/0666 and to a lesser extent L35/0205 were older than expected given the close proximity of these wells to the Selwyn River. Groundwater flow to these wells may be impeded by extensive claybound gravels.

In general, tritium gave the oldest groundwater age followed by CFC-11 then CFC-12 and SF_6 giving the youngest age. This trend could be attributable to either the behaviour of the different techniques (gases) through the unsaturated zone or the interaction of the gases with the atmosphere during transport through surface water bodies (rivers/creeks). The later process would account for the older than expected ages for wells L35/0666 and L35/0205.

Chapter Seven

Summary and Recommendations

7.1 Thesis Summary

The overall aim of this investigation was to obtain a comprehensive understanding of the surface and groundwater resources within the upper plains portion of the Selwyn catchment. Primary objectives included (1) Delineating the different aquifers and their properties (2) Establishing the relationship between surface water bodies and the groundwater resource (3) Establishing trends in groundwater chemistry both spatially and with depth (4) Distinguishing groundwater recharge sources through the use of water chemistry and/or oxygen-18 and (5) Determining the age of the groundwater resources.

7.1.1 Geology and geomorphology

The majority of the gravel deposits of the Selwyn Plains were formed during the late Quaternary period (approximately the last 400,000 years) when rapid uplift associated with the Kaikoura Orogeny, combined with glacial erosive processes, resulted in accelerated erosion of the Southern Alps. The eroded sediment and gravel was transported by east flowing rivers, largely during glacial periods, and deposited on the plains as fans. During glacial periods, large glaciers occupied the larger Waimakariri and Rakaia river valleys and extended to the eastern edge of the foothills. The smaller Selwyn River occupied the depression between the larger Waimakariri and Rakaia outwash fans.

Surface channel morphology between glacial Burnham gravels derived from the Selwyn River and those derived from the Rakaia and Waimakariri rivers are different. Surface channel morphologies of the Rakaia and Waimakariri rivers are typically fine-textured reflecting large braided river environments. In contrast, surface channelling in Selwyn River Burnham deposits are typically broader and more sinuous reflective of a meandering river system. These differences were critical in identifying surface gravels derived from the different rivers. These differences in surface morphology are likely to be reflected at depth, and groundwater is likely to flow preferentially through numerous small permeable remnant channels within Rakaia and Waimakariri glacial deposits, and through smaller and broader sinuous channels at depth within Selwyn Fan deposits.

The Hororata Fault coincides with river losses during normal flows within the Hawkins and Waianiwania rivers and is likely to have had a significant effect on the development of the groundwater system within the field area. Racecourse Hill is likely to be an uplifted block of Tertiary sediment capped by a thin veneer of Hororata Formation gravels and can be expected to locally have a significant effect on groundwater flow.

7.1.2 Surface hydrology and springs

7.1.2.1 Springs

The majority of springs within the field area are depression springs and outcrop within two distinct belts. One belt is located several hundred metres north of the Hororata River between Cotons Road and Derretts Road, the other belt is located east of Haldon Road.

Spring flow between Cotons Road and Derretts Road is permanent and likely to be sourced from surface losses from the Selwyn River shortly after Coalgate. Flow within all other springs is intermittent and strongly dependant on surface flows within nearby reaches of the Selwyn River.

7.1.2.2 Selwyn River

Gaugings along the Selwyn River show that significant surface losses occur within the upper reaches of the river between Coalgate and Bealey Road and further downstream between Greendale and Dunsandel. Water levels in shallow wells indicate that the river provides significant recharge to the shallow aquifer. Surface losses are strongly dependant on water table conditions but also depend on total flow and duration of flow peaks.

7.1.2.3 Hororata River

Gaugings along the Hororata River show that significant gains in surface flow occur between Derretts Road and the Selwyn confluence. The source for this increased flow is from numerous spring-fed creeks derived from surface losses from the Selwyn River. Water levels in shallow wells and visual observations of river flow suggest that the Hororata River significantly recharges the shallow aquifer south of the present course of the river.

7.1.2.4 Waianiwaniwa and Hawkins rivers

Both the Waianiwaniwa and Hawkins rivers generally lose all their surface flow to groundwater shortly after they emerge onto the Selwyn plains. Losses coincide with the intersection of the rivers with the Hororata Fault which indicates that the Hororata Fault has a significant influence on the groundwater system within the upper plains area. Water levels show that both rivers have a significant effect on adjacent shallow groundwater levels during flooding events within the rivers.

7.1.3 Hydrogeology

7.1.3.1 Aquifer identification

Cross-sections constructed from borelog descriptions, screen distributions and water levels show that at least three aquifers occur within the gravel deposits of the upper Selwyn plains. Aquifer 1 occurs between approximately 0 – 30m, aquifer 2 between 40-85m and aquifer 3 greater than 100m below the surface. The thickness of aquifer 3 could not be determined because of the lack of deep wells within the area. Aquifers 1 and 2 occur within close proximity to the Selwyn River and its tributaries. Aquifer 1 is unconfined, aquifer 2 semi-confined and aquifer semi-confined to confined. Significant leakage of groundwater occurs between the different aquifers.

Water levels within aquifer 2 become progressively lower with increasing distance inland with the lowest recorded water levels approaching the bottom of the aquifer. This suggests that wells penetrating aquifer 2 would have less available drawdown (and thus have a greater possibility of being less reliable) with progressive distance inland.

7.1.3.2 Groundwater flow

Piezometric contours show that groundwater flows in a general southeasterly direction within all three aquifers. Contours for aquifer 1 indicate that the Selwyn River provides significant recharge to the shallow aquifer in its upper reaches between Coalgate and Bealey Road. Similarly, contours along the lower reaches of the Hororata River indicate significant losses from the Hororata River to the shallow aquifer south of the Hororata River. Contours within aquifers 2 and 3 imply that these aquifers receive significant recharge from the Selwyn River south of the current location of the river.

7.1.3.3 Water level fluctuations

Groundwater fluctuations in shallow wells are greatest immediately adjacent to the Selwyn River which suggests the river has a significant effect on the surrounding shallow aquifer. With progressive distance from the river, fluctuations steadily decline and rainfall recharge becomes dominant. Water levels within wells close to the Waianiwaniwa River indicate that this river provides significant recharge to aquifers 1 and 2 during flood events.

Wells within the upper Selwyn plains are currently displaying a declining trend in groundwater levels with many wells reaching record low levels. This trend may reflect a long-term decrease in rainfall recharge to the aquifers or an increase in groundwater abstractions.

7.1.4 Groundwater chemistry

Water chemistry from selected wells, springs and rivers showed that some samples transgressed the 2000 New Zealand Drinking Water Standards for pH and nitrate-nitrogen. An area of nitrate-nitrogen elevated above half of the maximum acceptable value was identified in the Greendale area and is likely to be caused by agricultural activities upgradient of the source area.

Stiff plots showed that groundwater could be divided into a number of groups based on the similarity of the patterns. These Stiff plot patterns combined with chloride, nitrate-nitrogen (mg/L) and $\delta^{18}O$ concentrations enabled likely groundwater recharge sources to be identified. Dominantly river-recharged groundwater was identified extensively in aquifers 1 and 2 on the south of the present day Selwyn River. Dominantly rainfall-recharged groundwater was identified in aquifers 1 and 2 on the north side of the Selwyn River in the Greendale area. Other wells showed varying degrees of river and rainfall influence.

7.1.5 Groundwater ages

Overall, groundwater ages were older for deeper wells and areas inferred to be dominantly rainfall recharged from water chemistry and $\delta^{18}O$.

The old groundwater age for well L36/1635, together with low transmissivity values calculated for other wells at similar depths and location, imply careful management of the groundwater resources in that area. The groundwater ages for wells L35/0666 and to a lesser extent L35/0205 were older than expected given the close proximity of these wells to the Selwyn River. Groundwater flow to these wells may be impeded by extensive claybound gravels.

In general, tritium gave the oldest groundwater age followed by CFC-11 then CFC-12 and SF_6 giving the youngest age. This trend could be attributable to either the behaviour of the different techniques (gases) through the unsaturated zone or the interaction of the gases with the atmosphere during transport through surface water bodies (rivers/creeks).

7.2 Recommendations for future research

Work carried out during this research identified a number of areas where future research could help to better understand the water resources of the area. Recommendations for future monitoring include:

- Monthly oxygen-18 sampling of the Selwyn and Hororata rivers, and a few selected wells of different depths, to better establish short-term, seasonal and long-term trends.

- Age dating of the Selwyn River at Coalgate, this would identify the time it takes for rainfall infiltration, within the foothills catchment, to reach the Selwyn River. Age dating of wells L35/0666, L36/0579 and the Hororata River downstream from Haldon Road, to better understand the trend in groundwater ages given by the different age dating techniques (i.e. the pattern of tritium giving the oldest groundwater age followed by CFC-11 then CFC-12 and SF6 giving the youngest age) and to establish whether ages are reset or partially rest when groundwater enters a surface water body.

- The establishment of a monthly well run using wells measured during this research to better understand groundwater level trends and likely recharge sources.

- Further monitoring of nitrates within the Greendale area.

- Set up of an automatic flow recorder on the Hororata Rver shortly after the addition of permanent spring-fed creeks. This would give a better understanding of the correlation between flow gains within the Hororata River downstream from Derretts Road, flow losses within the Selwyn River downstream from Coalgate, and the influence of rainfall recharge to the shallow groundwater system between the Selwyn and Hororata rivers.

- The use of geophysics to determine (1) whether the Hororata Fault affects groundwater flow and (2) the lateral and vertical extent of Tertiary rocks near Racecourse Hill.

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Appendix 2.1

"Borelogs for selected wells near Racecourse Hill: locations are shown in geological map (figure 2.9 – back pocket)"

Borelog for well L35/0323

Gridref: L35:3442-5130 Accuracy : 3 (1=best, 4=worst)
Ground Level Altitude : 245 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -36m Drill Date : 1/10/1987

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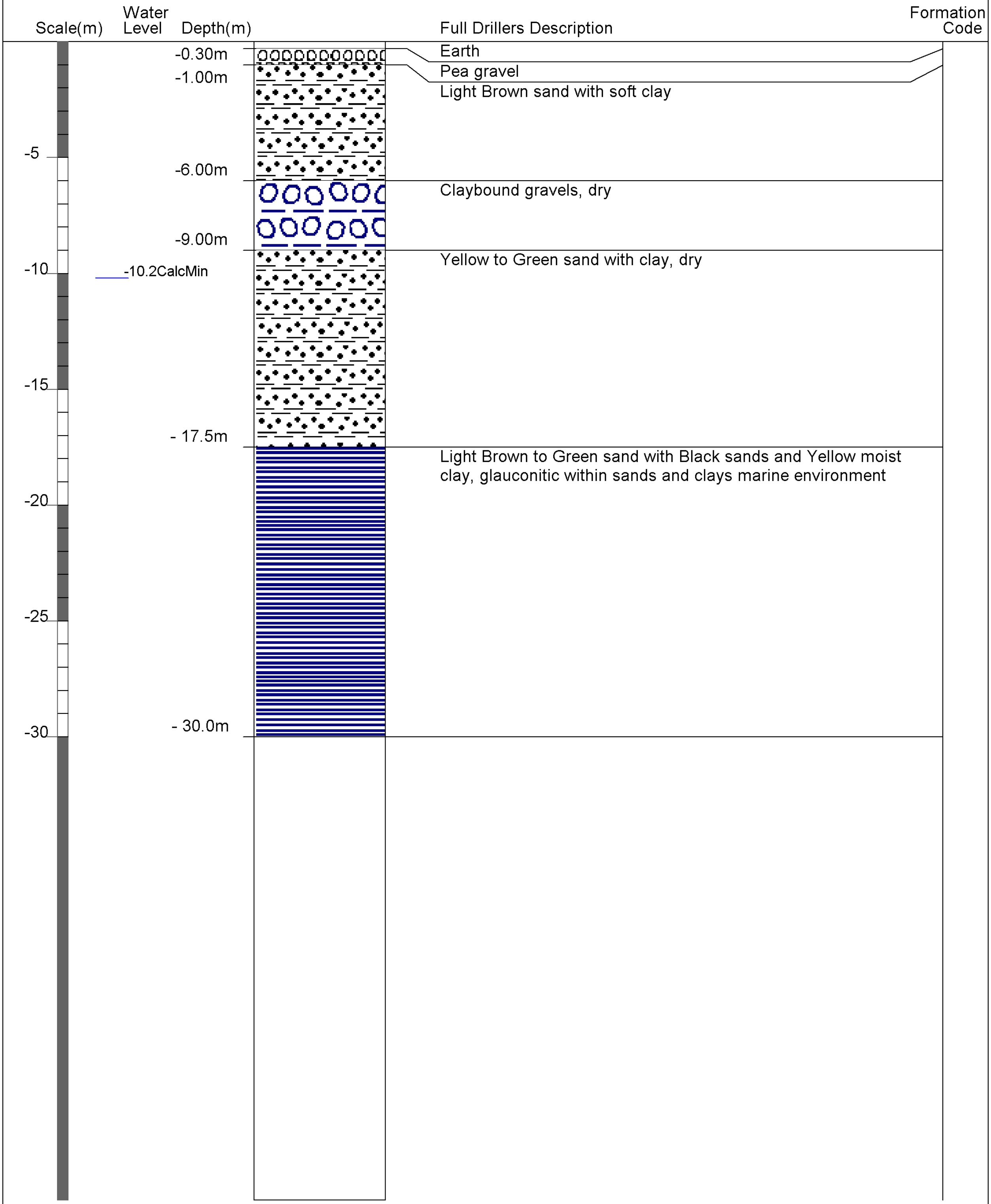
Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
		-0.20m	Earth	
		-1.00m	Clay	
-5		-4.00m	Large Grey gravel	
-10	-8.3CalcMin	-9.00m	Tight claybound gravel	
		- 11.0m	Dark Brown clay	
-15, -20, -25		- 29.0m	Brown quartz and fine sand, glauconitic, marine environment, looks similar to Kaiteriteri sands	
-30, -35		- 36.0m	Fine Brown sands	

Borelog for well L35/0324

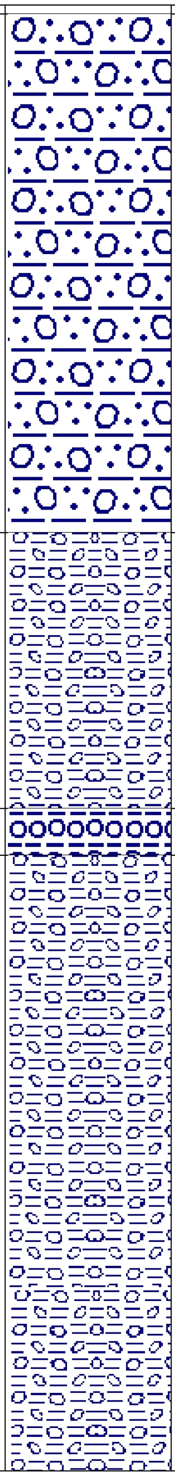
Gridref: L35:3448-5085 Accuracy : 3 (1=best, 4=worst)
Ground Level Altitude : 246 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -30m Drill Date : 1/10/1987



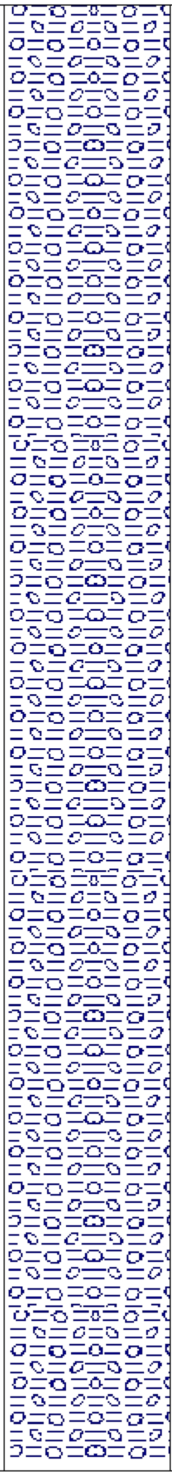
Borelog for well L35/0325 page 1 of 6

Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
			Earth	
		-0.30m	Medium sized gravels dry clay and sand	
-5				
-10				
-15				
		- 18.0m	Small Grey gravels and Brown clay	
-20				
-25				
		- 27.4m	Light Brown clay pliable with small gravel chips and silts	
		- 29.0m	Small gravels and clay	
-30				
-35				
-40				
-45				
		- 160.0m		



Borelog for well L35/0325 page 2 of 6
Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

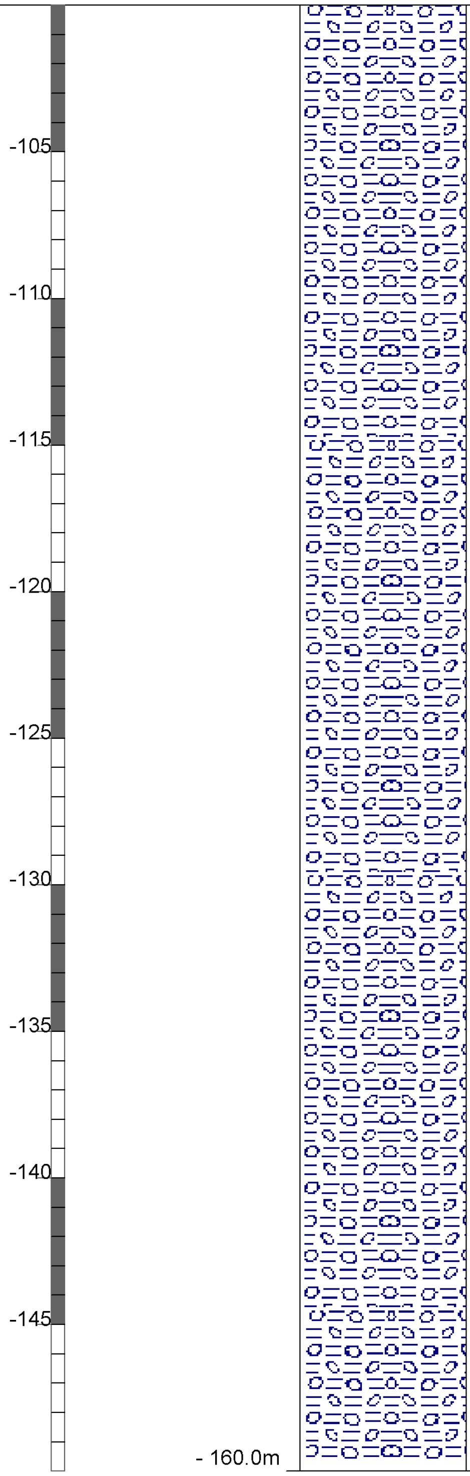
Scale(m)	Water Level	Depth(m)		Full Drillers Description	Formation Code
-55 -60 -65 -70 -75 -80 -85 -90 -95		- 160.0m		Small gravels and clay	

Borelog for well L35/0325 page 3 of 6

Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Environment Canterbury
Your regional council

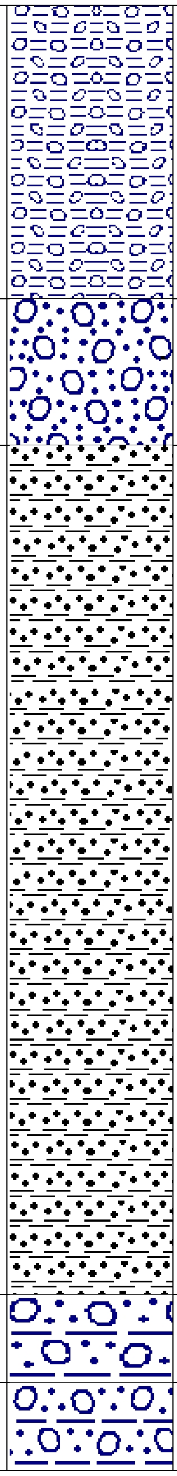
Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
			Small gravels and clay	



Borelog for well L35/0325 page 4 of 6

Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Scale(m): -155, -160, -165, -170, -175, -180, -185, -190, -195



Water Level	Depth(m)	Full Drillers Description	Formation Code
	- 160.0m	Small gravels and clay	
	- 165.0m	Small pebbles with coarse sand	
	- 194.0m	Yellow sandy clay	
	- 197.0m	Coarse Yellow sandy clay with fine gravels	
	- 249.0m	Yellow clay and sandy gravel	

Borelog for well L35/0325 page 5 of 6

Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
-205, -210, -215, -220, -225, -230, -235, -240, -245			Yellow clay and sandy gravel	
		- 249.0m		
		- 255.0m	Yellow clay and sandy gravel	

Borelog for well L35/0325 page 6 of 6

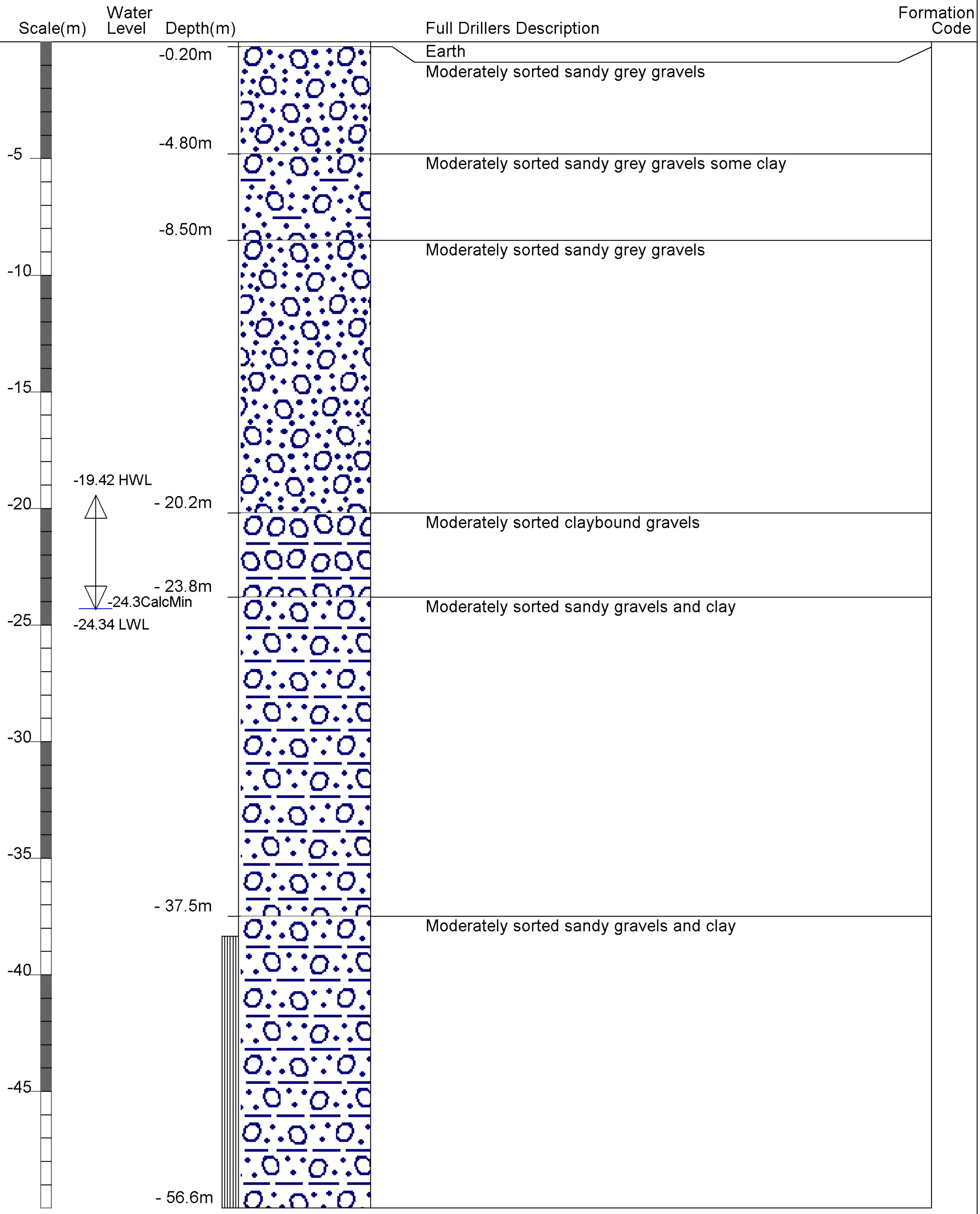
Gridref: L35:3431-4992 Accuracy : 4 (1=best, 4=worst)
Ground Level Altitude : 236 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -255m Drill Date : 1/12/1987

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
-255		- 255.0m	Yellow clay and sandy gravel	

Borelog for well L35/0727 page 1 of 2

Gridref: L35:35864-54960 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 259.97 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -71m Drill Date : 8/08/2001

Environment Canterbury
Your regional council



Borelog for well L35/0727 page 2 of 2

Gridref: L35:35864-54960 Accuracy : 1 (1=best, 4=worst)
Ground Level Altitude : 259.97 +MSD
Driller : McMillan Water Wells Ltd
Drill Method : Rotary/Percussion
Drill Depth : -71m Drill Date : 8/08/2001

Environment Canterbury
Your regional council

Scale(m)	Water Level	Depth(m)	Full Drillers Description	Formation Code
-55		- 56.6m	Moderately sorted sandy gravels and clay	
-60		- 63.0m	Moderately sorted sandy gravels and clay	
-65		- 68.5m	Fine brown sand and small quartz gravels	
-70		- 71.0m	Greenish sand and traces of white clayish siltsone	

Appendix 3.1

"Spring Classification Criteria and Illustrations of Spring Types and Morphology"

Spring Classification

Spring Types

Depression Spring – a spring that is formed when the water table intercepts the land surface, usually in a topographically low position.

Contact Spring – a spring that forms when groundwater flowing in a permeable formation comes into contact with underlying less permeable material which impedes the flow of groundwater.

Artesian Spring – a springs that flows freely above the land surface from an aquifer that is under artesian pressure.

Fault Spring – a spring that is formed when a permeable faulted unit is brought into contact with a less permeable unit resulting in the formation of an impermeable boundary. The impermeable boundary forces the groundwater to flow along the fault plane to a more permeable zone where the spring is discharged.

Joint/Fracture Spring – a spring that flows along a rock defect such as a fracture or a joint usually in a low permeable rock unit. Spring discharge occurs where the fractures and/or joints intersect the land surface.

Sinkhole Spring – a spring where water dissolves limestone beneath the surface and creates a sinkhole that intersects the water table.

Spring Morphology

Seepage – a spring where there is no observable point or source where discharge is flowing from.

Point-source – a spring that discharges from an observable point or source.

Linear/Channel – a spring in which discharge is flowing along the length of a channel.

Horizon – a spring that originates from a particular lithologic unit and can be followed along the length of that horizon.

Discharge Variability

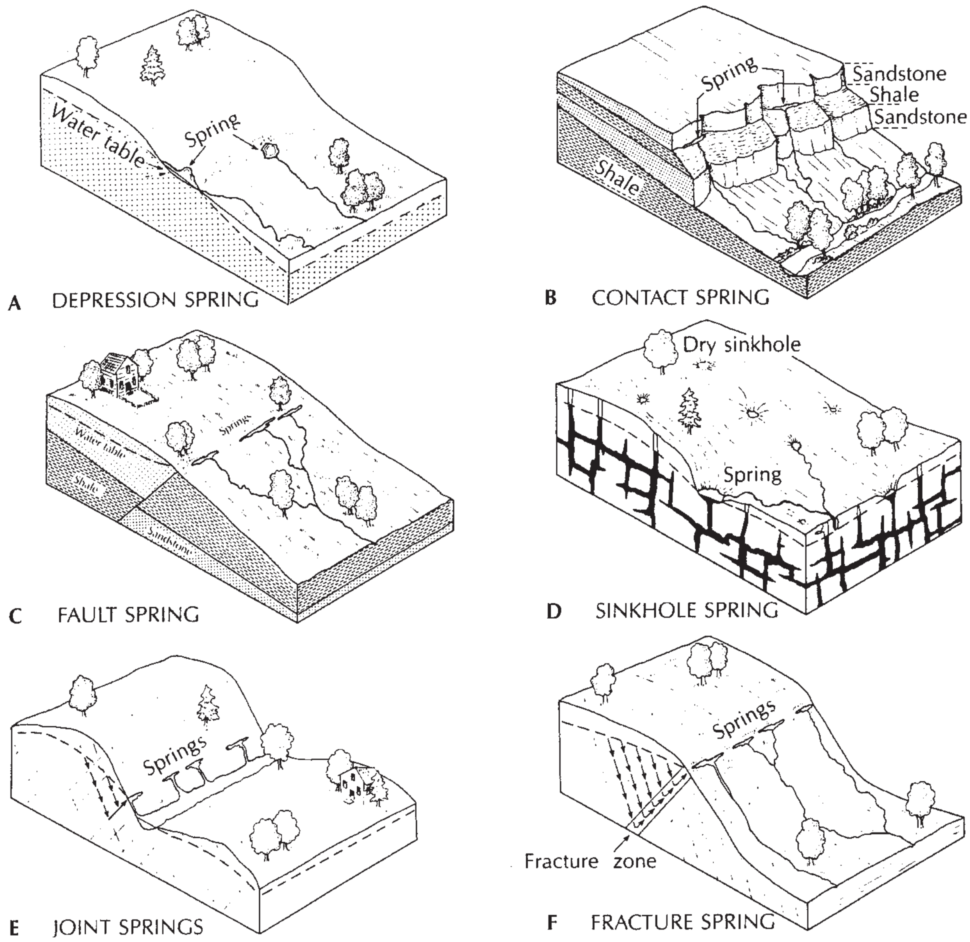
Permanent – spring flows all year round.

Intermittent – spring flows seasonally, or with antecedent conditions such as rainfall or river flow.

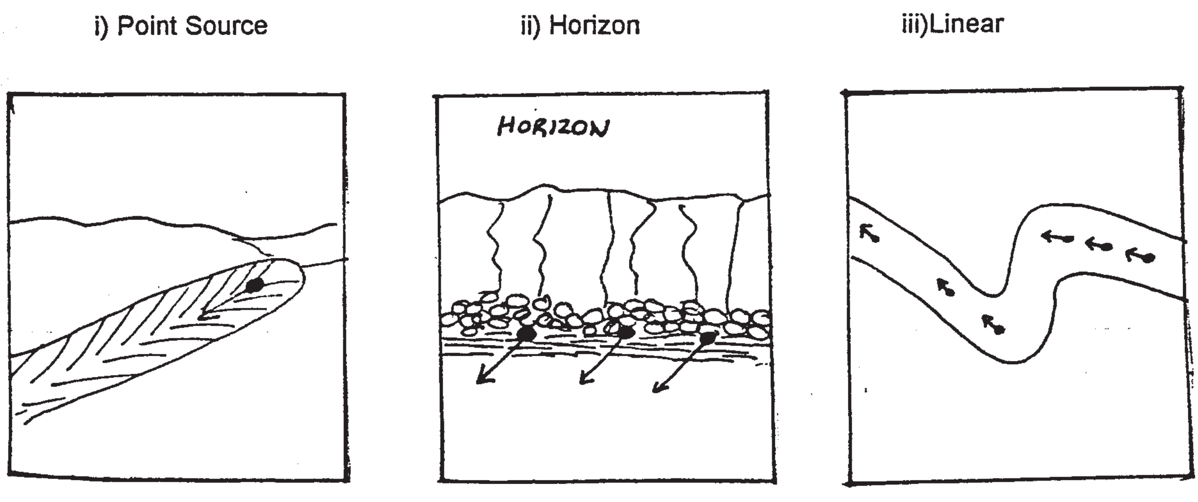
Unknown – spring not observed long enough to classify as permanent or intermittent.

Geology Type - the geology where the spring emerges i.e. gravel, soil, silt, sand, mud, etc.

Spring Types (from Fetter, 2001)



Spring Morphology (from Earl, 1997)



Appendix 3.2

"Visual Observations of Flow for the Selwyn, Hororata, Waianiwaniwa and Hawkins Rivers at Various Locations Between June 2004 and May 2005"

Flow Observations for Selwyn River

Date	A	B	C	D	E	F	G	H	I	J	K
2/06/2004	Flowing	Flowing	Flowing	?	DRY	DRY	?	?	?	?	?
30/07/2004	Flowing	Flowing	Flowing	Flowing	Flowing	?	Flowing	?	?	DRY	DRY
14/08/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing
30/08/2004	Flowing	Flowing	Flowing	Flowing	Flowing	?	?	?	?	?	?
7/09/2004	3.442	3.365	2.836								
8/09/2004				Flowing	0.579	0.320	2.634	Flowing	Flowing	0.798	?
30/09/2004	Flowing	Flowing	Flowing	Flowing	Flowing	?	Flowing	?	?	?	?
24/09/2004	2.675	2.476	1.888	Flowing	DRY	DRY	1.748	Flowing		DRY	DRY
25/09/2004									0.245		
6/10/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing
20/10/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	DRY
22/10/2004	2.790	2.473	2.012	Flowing	0.199	0.054	1.899	Flowing	0.305	DRY	DRY
5/11/2004	2.140	1.950	1.401	Flowing	0.01(VE)	DRY	1.504	Flowing	DRY	DRY	DRY
19/11/2004	Flowing	Flowing	Flowing	?	DRY	DRY	Flowing	?	?	?	?
3/12/2004	Flowing	Flowing	Flowing	?	DRY	DRY	Flowing	Flowing	DRY	DRY	DRY
15/12/2004	1.490	1.260	0.762	DRY	DRY	DRY	0.435	Flowing	DRY	DRY	DRY
30/12/2004	Flowing	Flowing	Flowing	Flowing	Flowing	DRY	Flowing	Flowing	DRY	DRY	DRY
14/01/2005	Flowing	Flowing	Flowing	Flowing	Flowing	DRY	Flowing	Flowing	Flowing	DRY	DRY
27/01/2005	Flowing	Flowing	Flowing	DRY	DRY	DRY	Flowing	Flowing	DRY	DRY	DRY
10/02/2005	Flowing	Flowing	?	DRY	DRY	DRY	Flowing	DRY	DRY	DRY	DRY
24/02/2005	Flowing	Flowing	DRY	DRY	DRY	DRY	Flowing	DRY	DRY	DRY	DRY
10/03/2005	Flowing	Flowing	DRY	DRY	DRY	DRY	Trickle	DRY	DRY	DRY	DRY
24/03/2005	Flowing	Flowing	DRY	DRY	DRY	DRY	DRY?	DRY	DRY	DRY	DRY
7/04/2005	Flowing	Flowing	Flowing	DRY	DRY	DRY	DRY?	DRY	DRY	DRY	DRY
28/04/2005	Flowing	Flowing	Flowing	DRY	DRY	DRY	DRY?	DRY	DRY	DRY	DRY

A Whitecliffs Recorder Site
B Coalgate Bridge
C Scotts Rd
D Hawkins Rd
E Bealey Rd
F Gillanders Rd

G Ridgens Rd
H Westenras Rd
I Old South Rd
J Highfield Rd
K SH 1

(shaded) Gauged (with flow in m^3/s)

VE Visual Estimate

Flow Observations for Hororata River

Date	A	B	C	D	E	F	G
1/07/2004	Flowing	Flowing	Flowing	Flowing	?	DRY	?
14/08/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	?
9/09/2004	0.353	0.201	0.340	0.329	1.159	1.741	2.300
24/09/2004							1.657
25/09/2004	0.465	0.273	0.225	0.193	0.819	0.877	
20/10/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing
21/10/2004	0.330	0.232	0.390	0.323	0.911	Flowing	1.924
5/11/2004	0.177	0.047	0.233	0.118	0.713	Flowing	1.342
14/12/2004	0.173	0.043	0.196	0.071	0.507	0.064	0.435
30/12/2004	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing	Flowing
14/01/2005	Flowing	?	Flowing	Flowing	Flowing	Flowing	Flowing
27/01/2005	Flowing	?	Flowing	Flowing	Flowing	Flowing	Flowing
4/02/2005	Flowing	DRY	Flowing	Ponding	Flowing	?	Flowing
10/02/2005	Flowing	DRY	Flowing	DRY	Flowing	?	Flowing
24/02/2005	Flowing	DRY	Flowing	DRY	Flowing	DRY	Flowing
10/03/2005	Flowing	DRY	Flowing	DRY	Flowing	DRY	Flowing
24/03/2005	Flowing	DRY	Flowing	DRY	Flowing	DRY	Trickle
7/04/2005	Flowing	Flowing	Flowing	DRY	Flowing	DRY	DRY
28/04/2005	Flowing	Trickle	Flowing	DRY	Flowing	DRY	DRY

A Sleemans Rd
B Milnes Rd
C Cotons Rd
D Derretts Rd
E Haldon Rd
F Gillanders Rd
G Selwyn Confluence

Gauged (with flow in m3/s)

Flow Observations for Hawkins River

Date	A	B	C	D	E
18/05/2004	Flowing	Flowing	DRY	DRY	DRY
2/06/2004	Flowing	Flowing	DRY	DRY	DRY
13/08/2004	Flowing	Flowing	Flowing	Flowing	Flowing
14/08/2004	Flowing	Flowing	?	?	DRY
19/08/2004	Flowing	Flowing	?	DRY	DRY
30/08/2004	Flowing	Flowing	?	DRY	DRY
6/10/2004	Flowing	Flowing	DRY	DRY	DRY
2/12/2004	Flowing	Flowing	DRY	DRY	DRY
30/12/2004	Flowing	Flowing	DRY	DRY	DRY
14/01/2005	Flowing	Flowing	DRY	DRY	DRY
28/01/2005	Flowing	Flowing	DRY	DRY	DRY
1/02/2005	Flowing	Flowing	DRY	DRY	DRY
10/02/2004	Flowing	DRY	DRY	DRY	DRY
25/02/2005	Flowing	DRY	DRY	DRY	DRY
10/03/2005	Flowing	DRY	DRY	DRY	DRY
24/03/2005	Flowing	DRY	DRY	DRY	DRY
7/04/2005	Pooling	DRY	DRY	DRY	DRY
29/04/2005	Flowing	?	DRY	DRY	DRY
20/05/2004	Flowing	Flowing	DRY	DRY	DRY

A Deans Rd
B Auchenflower Rd
C Bangor Rd
D Bealey Rd
E Coaltrack Rd

Flow Observations for Wainiwaniwa River

Date	A	B	C	D	E
02/06/04	Flowing	DRY	DRY	DRY	DRY
04/06/04	Flowing	DRY	DRY	DRY	DRY
08/06/04	Flowing	DRY	DRY	DRY	DRY
12/08/04	Flowing	Flowing	Flowing	Flowing	DRY
13/08/04	Flowing	Flowing	Flowing	Flowing	Flowing
14/08/04	Flowing	Flowing	Flowing	Flowing	DRY
19/08/04	Flowing	Flowing	Flowing	Flowing	Flowing
30/08/04	Flowing	?	?	DRY	DRY
08/09/04	Flowing	Flowing	Flowing	?	?
23/09/04	Flowing	Flowing	Flowing	?	?
06/10/04	Flowing	?	?	?	?
22/10/04	Flowing	Flowing	Flowing	?	?
19/11/04	Flowing	Flowing	Flowing	?	?
02/12/04	Flowing	?	DRY	DRY	DRY
16/12/04	Flowing	?	DRY	DRY	DRY
30/12/04	Flowing	?	DRY	DRY	DRY
14/01/05	?	?	DRY	DRY	DRY
28/01/05	?	?	DRY	DRY	DRY
01/02/05	DRY	DRY	DRY	DRY	DRY
10/02/05	DRY	DRY	DRY	DRY	DRY
25/02/05	DRY	DRY	DRY	DRY	DRY
10/03/05	DRY	DRY	DRY	DRY	DRY
24/03/05	DRY	DRY	DRY	DRY	DRY
07/04/05	DRY?	DRY	DRY	DRY	DRY
20/05/05	?	?	DRY	DRY	DRY

A Homebush Rd
B Beattys Rd
C Waireka Rd
D Bealey Rd
E Coaltrack Rd

Appendix 3.3

"Flow gauging results for the Selwyn and Hororata rivers conducted during this study"

Selwyn River Flow Gauging Results (m^3/s)										
	Gauging Locations									
	S1 (Whitecliffs)	**SDC1*** (Glentunnel)	**SDC2*** (Coalgate)	**S2** (Coalgate)	**S3** (Scotts road)	**S4** (Bealey road)	**S5** (Gillanders road)	**S6** (Ridgens road)	**S7** (Old South road)	**S8** (Highfield road)
Run 1 (07/09/04 & 08/09/04)	3.44	0.16	0.09	3.37	2.84	0.58	0.32	2.63	1.06	0.80
Run 2 (24/09/04 & 25/09/04)	2.68	0.16	0.09	2.48	1.89	Dry	Dry	1.75	0.25	Dry
Run 3 (22/10/04)	2.79	0.16	0.09	2.47	2.01	0.20	0.05	1.90	0.31	Dry
Run 4 (5/11/04)	2.14	0.16	0.09	1.95	1.40	0.01	Dry	1.50	Dry	Dry
Run 5 (15/12/04)	1.49	0.16	0.09	1.26	0.76	Dry	Dry	0.44	Dry	Dry

* Surface abstractions from the Selwyn river at SDC1 (Selwyn District Council stock water intake at Glentunnel) and SDC2 (Selwyn District Council stock water intake upstream of Coalgate gauging site (S2)) were based on consented flows and were not gauged.

Hororata River Flow Gauging Results (m^3/s)							
	Gauging Locations						
	H1 (Sleemans road))	**H2** (Milnes road)	**H3** (Cotons road)	**H4** (Derretts road)	**SDC3*** (Haldon road))	**H5** (Haldon road)	**H6** (Selwyn confl.)
Run 1 (09/09/04)	0.35	0.20	0.34	0.33	0.09	1.16	2.30
Run 2 (25/09/04)	0.47	0.27	0.23	0.19	0.09	0.82	1.66
Run 3 (21/10/04)	0.33	0.23	0.39	0.32	0.14	0.91	1.92
Run 4 (5/11/04)	0.18	0.05	0.23	0.12	0.14	0.71	1.34
Run 5 (14/12/04)	0.17	0.04	0.20	0.07	0.14	0.51	0.44

* Surface abstractions from the Hororata river at SDC3 (Selwyn District Council stock water intake 500m upstream of Haldon roadl) are based on gaugings and staff gauge readings at this site.

Appendix 4.1

"Transmissivity and Storativity data for wells within the field area"

Well Number	Depth (m)	Transmissivity (m2/day)	Storativity	Leakage (m)	K'/B'
L35/0751	39.6	12400	0.002		
L35/0754	56.1	646	0.0004		
L35/0754	56.1	670	0.0003	1950	1.76E-04
L36/0058	82.9	1043			
L36/0058	82.9	1043			
L36/0063	56.3	2339			
L36/0063	56.3	2636			
L36/0064	89.0	300			
L36/0065	61.7	24500			
L36/0066	51.2	700			
L36/0066	51.2	1221			
L36/0066	51.2	3116			
L36/0068	49.0	2200			
L36/0086	62.1	8000			
L36/0122	24.0	1615			
L36/0183	39.6	968			
L36/0206	14.3	4776			
L36/0293	11.6	15005			
L36/1028	94.3	13200			
L36/1107	53.2	3660	0.00022	4150	2.13E-04
L36/1109	68.1	9400			
L36/1226	109.3	900			
L36/1334	99.0	10700	0.00014	17000	3.70E-05
L36/1334	99.0	1700			
L36/1492	101.3	2990	0.0002	2564	4.55E-04
L36/1492	101.3	6300			
L36/1492	101.3	6300			
L36/1529	96.1	5000			
L36/1530	84.4	8570			
L36/1562	71.0	11500	0.00005	15000	5.11E-05
L36/1576	84.0	7390	0.00016	2910	8.73E-04
L36/1700	112.7	5110			

Appendix 4.2

"Details and elevations for piezometric survey wells"

Piezometric well details - Aquifer 1

Well No	Grid east	Grid north	Depth	Measuring Point Elevation (m)	Depth to water (m)	Piezometric surface elevation (m)
L35/0013	2423923	5740146	8.2	192.2	-4.3	187.9
L35/0148	2424907	5742425	9.7	200.1	-8.2	191.9
L35/0168	2431692	5752524	11.0	261.2	-4.2	257.1
L35/0177	2431050	5756698	10.1	290.9	-3.6	287.3
L35/0180	2434001	5752317	7.5	255.5	-6.0	249.5
L35/0183	2431712	5755712	4.1	283.8	-2.5	281.2
L35/0184	2431488	5751239	15.2	252.9	-4.6	248.3
L35/0205	2430392	5742194	28.0	187.2	-9.7	177.4
L35/0315	2432707	5754472	12.0	275.0	-4.8	270.3
L35/0550	2428422	5741192	32.9	188.6	-7.8	180.8
L35/0585	2425713	5740360	4.6	183.9	-3.9	180.0
L35/0596	2433170	5753743	17.2	268.1	-7.3	260.8
L35/0666	2426698	5740991	34.6	187.6	-10.8	176.7
L36/0003	2422805	5738170	11.2	203.6	-9.7	194.0
L36/0014	2416403	5739528	19.2	269.6	-12.7	257.0
L36/0016	2415159	5739845	12.1	287.5	-5.8	281.8
L36/0021	2427719	5739714	24.6	176.3	-4.5	171.8
L36/0026	2426085	5739858	12.0	178.7	-1.7	177.0
L36/0033	2435940	5734247	6.1	128.5	-1.9	126.7
L36/0034	2436395	5735389	15.1	131.3	-15.0	116.3
L36/0039	2436874	5736519	22.3	138.3	-17.8	120.5
L36/0042	2437303	5733881	10.1	121.3	-6.9	114.4
L36/0043	2435337	5735767	16.0	136.2	-15.0	121.2
L36/0046	2433520	5736771	16.8	144.6	-8.4	136.2
L36/0047	2435725	5732493	6.0	121.6	-3.4	118.2
L36/0051	2439255	5732798	22.9	106.8	-3.7	103.2
L36/0054	2439154	5730768	15.1	104.8	-3.5	101.3
L36/0122	2439632	5729024	24.0	99.1	-4.7	94.4
L36/0139	2445213	5728929	15.7	78.7	-12.5	66.2
L36/0182	2442741	5728035	19.5	85.4	-4.5	80.9
L36/0186	2441160	5728893	6.7	93.2	-3.6	89.6
L36/0206	2440491	5729470	14.3	97.0	-3.6	93.4
L36/0311	2446197	5728915	18.0	74.2	-11.8	62.4
L36/0317	2436514	5734991	24.4	129.2	-11.9	117.3
L36/0327	2438120	5730184	15.1	107.2	-4.5	102.7
L36/0377	2438178	5733182	7.1	112.3	-2.0	110.3
L36/0394	2435246	5731949	18.3	124.2	-6.3	117.9
L36/0436	2439338	5729803	18.0	102.3	-4.6	97.7
L36/0490	2427004	5739790	7.5	177.3	-3.1	174.2
L36/0494	2438493	5731685	11.5	109.1	-3.0	106.1
L36/0495	2440207	5730313	11.5	98.7	-2.3	96.4
L36/0497	2442013	5729119	15.0	91.5	-4.8	86.7
L36/0543	2437810	5731616	15.2	112.1	-3.8	108.4
L36/0579	2434515	5732454	20.0	128.5	-5.9	122.6
L36/0585	2426775	5738605	10.4	172.5	-10.4	162.2
L36/0647	2423971	5739464	7.6	193.2	-5.0	188.2
L36/0737	2429866	5737535	12.0	161.0	-3.2	157.8
L36/0805	2433781	5732575	24.0	132.9	-9.8	123.0
L36/1111	2438188	5729297	20.0	106.4	-8.7	97.7
L36/1182	2431608	5738573	18.0	161.7	-9.6	152.1

L36/1189	2429192	5739073	12.0	170.5	-5.0	165.5
L36/1193	2430733	5738797	6.5	164.5	-5.8	158.7
L36/1475	2441399	5730841	15.7	96.3	-6.4	89.9
L36/1557	2430319	5737284	3.0	159.0	-3.0	156.0
L36/1692	2411861	5738726	5.0	317.7	-3.1	314.6
L36/1896	2431500	5737787	5.0	155.7	-4.6	151.1
L36/1902	2421172	5739847	3.0	227.9	-2.6	225.3
L36/1904	2422347	5739980	5.0	212.1	-1.7	210.4
L36/1909	2420307	5738581	11.0	228.7	-10.1	218.6
L36/0785	2432107	5732696	35.0	142.9	-21.5	121.4
L35/0206	2431471	5740232	30.0	171.3	-13.4	157.9
L35/0600	2426989	5742579	32.0	203.3	-18.0	185.2
L35/0154	2428504	5744202	27.0	207.6	-16.7	190.9
L35/0353	2430339	5746712	30.0	213.3	-14.8	198.5
L35/0620	2431675	5745174	23.5	204.0	-18.3	185.7

Piezometric well details - Aquifer 2

Well No	Grid east	Grid north	Depth	Measuring Point Elevation (m)	Depth to water (m)	Piezometric surface elevation (m)
L35/0152	2425852	5742522	38.4	203.9	-20.5	183.4
L35/0171	2432428	5745902	53.8	210.0	-44.2	165.8
L35/0247	2426274	5742150	26.5	200.5	-17.8	182.7
L35/0274	2431218	5742041	25.0	182.9	-20.7	162.1
L35/0578	2431916	5757562	61.0	296.2	-22.8	273.4
L35/0679	2435538	5754532	54.0	260.1	-17.1	243.0
L35/0727	2435864	5754960	54.3	260.3	-24.0	236.2
L36/0059	2430571	5734282	47.2	152.4	-33.6	118.8
L36/0062	2432582	5738811	25.0	160.1	-18.1	142.0
L36/0065	2439474	5736997	61.7	135.3	-49.3	86.0
L36/0066	2436977	5735512	51.2	131.1	-30.9	100.2
L36/0076	2436863	5737647	63.4	144.4	-49.2	95.2
L36/0090	2440127	5735065	54.0	120.8	-38.3	82.4
L36/0092	2444108	5736099	60.6	119.1	-50.2	68.9
L36/0124	2436559	5727261	35.0	112.4	-27.9	84.5
L36/0181	2442745	5728035	75.0	85.7	-14.8	70.8
L36/0205	2446144	5728802	81.4	74.6	-14.7	59.8
L36/0303	2431996	5722621	66.0	128.8	-58.1	70.7
L36/0428	2442966	5734011	54.5	110.2	-37.1	73.1
L36/0486	2441417	5728068	76.2	90.3	-15.3	75.0
L36/0680	2441154	5728941	69.5	94.2	-16.2	78.0
L36/0874	2432348	5739401	29.1	164.4	-18.3	146.1
L36/1006	2438333	5737943	55.0	144.8	-50.6	94.2
L36/1107	2436726	5731882	53.2	116.9	-28.5	88.4
L36/1109	2435324	5730686	68.1	124.6	-36.7	87.9
L36/1188	2440560	5729395	77.0	97.1	-17.7	79.3
L36/1207	2438341	5738552	63.5	148.1	-57.6	90.5
L36/1265	2434402	5737660	54.0	150.4	-35.5	114.9
L36/1322	2437696	5728889	71.0	108.6	-26.3	82.3
L36/1396	2439556	5728200	62.0	96.9	-18.3	78.6
L36/1474	2441444	5730865	78.2	95.9	-19.4	76.5
L36/1562	2436326	5730252	71.0	117.6	-31.1	86.5
L36/1564	2446196	5730418	45.0	80.6	-19.5	61.1
L36/1566	2445228	5728798	91.0	78.3	-16.4	61.9
L36/1650	2435999	5730977	78.0	119.7	-32.1	87.7
L36/1709	2436992	5731543	63.6	115.1	-27.4	87.7
L36/1745	2441419	5736593	65.7	128.9	-50.5	78.4
L36/0063	2439441	5735661	56.3	126.2	-41.0	85.2

Piezometric well details - Aquifer 3

Well No	Grid east	Grid north	Depth	Measuring Point Elevation (m)	Depth to water (m)	Piezometric surface elevation (m)
L35/0204	2431175	5742014	127.4	183.1	-68.9	114.2
L35/0208	2433690	5741062	125.0	171.2	-71.7	99.5
L35/0542	2440536	5741620	100.0	163.5	-81.9	81.6
L35/0598	2437610	5743858	120.0	185.7	-95.4	90.3
L36/0023	2425291	5725408	109.5	170.2	-80.2	90.0
L36/0064	2435586	5737501	89.0	147.5	-54.2	93.3
L36/1081	2427434	5735209	116.0	173.5	-77.6	95.9
L36/1110	2437368	5740088	158.8	160.0	-78.3	81.7
L36/1157	2425670	5729153	102.0	181.8	-90.7	91.1
L36/1226	2423827	5736207	109.3	198.7	-97.4	101.3
L36/1485	2424920	5737874	168.0	188.1	-87.6	100.4
L36/1635	2426705	5737881	131.9	175.5	-77.6	97.9
L36/1689	2417234	5733237	211.0	242.3	-128.8	113.5
L36/1693	2438435	5739145	205.5	152.7	-71.3	81.4
L36/1700	2431440	5737739	112.7	155.8	-58.8	97.0
L36/1749	2440214	5739608	107.3	150.7	-70.4	80.3
L36/1762	2432472	5739291	119.7	163.6	-64.8	98.9
L36/1814	2435588	5731645	88.0	122.7	-33.9	88.8
L36/1666	2425268	5737275	126.0	185.7	-87.0	98.7
L36/1498	2428160	5725410	148.0	156.0	-80.0	76.0
L35/0756	2441770	5743230	119.0	170.0	-91.3	78.8
L36/1351	2441662	5732711	64.7	101.0	-34.8	66.2
L36/1530	2433570	5734947	84.4	137.2	-43.8	93.3

Appendix 5.1

"Guideline and Maximum Acceptable Values for selected determinands based on the 2000 Drinking Water Standards for New Zealand (Ministry of Health, 2000)"

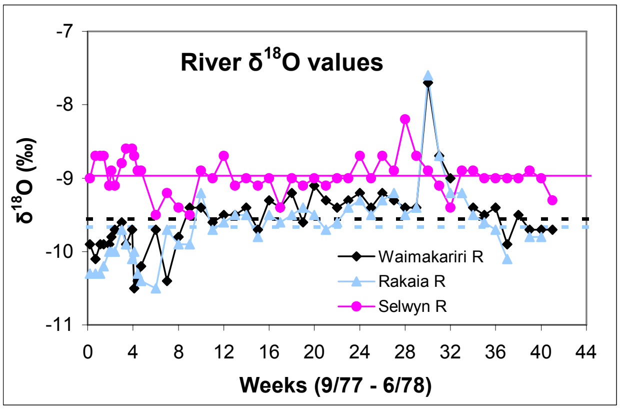
Determinand in milligrams per litre (mg/L) unless otherwise specified	**Maximum Guideline Value (or acceptable range) on basis of aesthetic effects**	**Maxiumum Acceptable Value (MAV) on basis of health effects**	**Typical range of values in Canterbury Groundwater from gravel aquifers**
pH	6.5 to 8.5 (preferred range between 7.0 and 8.0)		Shallow groundwater (<30m) 6.0 - 7.8 Deeper groundwater 6.7 - 7.9
Conductivity(mS/m)			5 - 45
Nitrate Nitrogen		11.3	0.1 - 12
Calcium			8 – 43
Magnesium			1 – 12
Sodium	200		3 – 36
Pottassium			0.7 – 3
Iron	0.2		0.1 – 2
Manganese	0.05	0.5	0.02 – 2
Sulphate	250		1.8 – 31
Chloride	250		2 – 46
Alkalinity			50 – 185
Hardness	200		28 - 140

Appendix 5.2

"Raw $\delta^{18}O$ data for the Waimakariri, Rakaia and Selwyn rivers sampled between September 1977 and June 1978 "

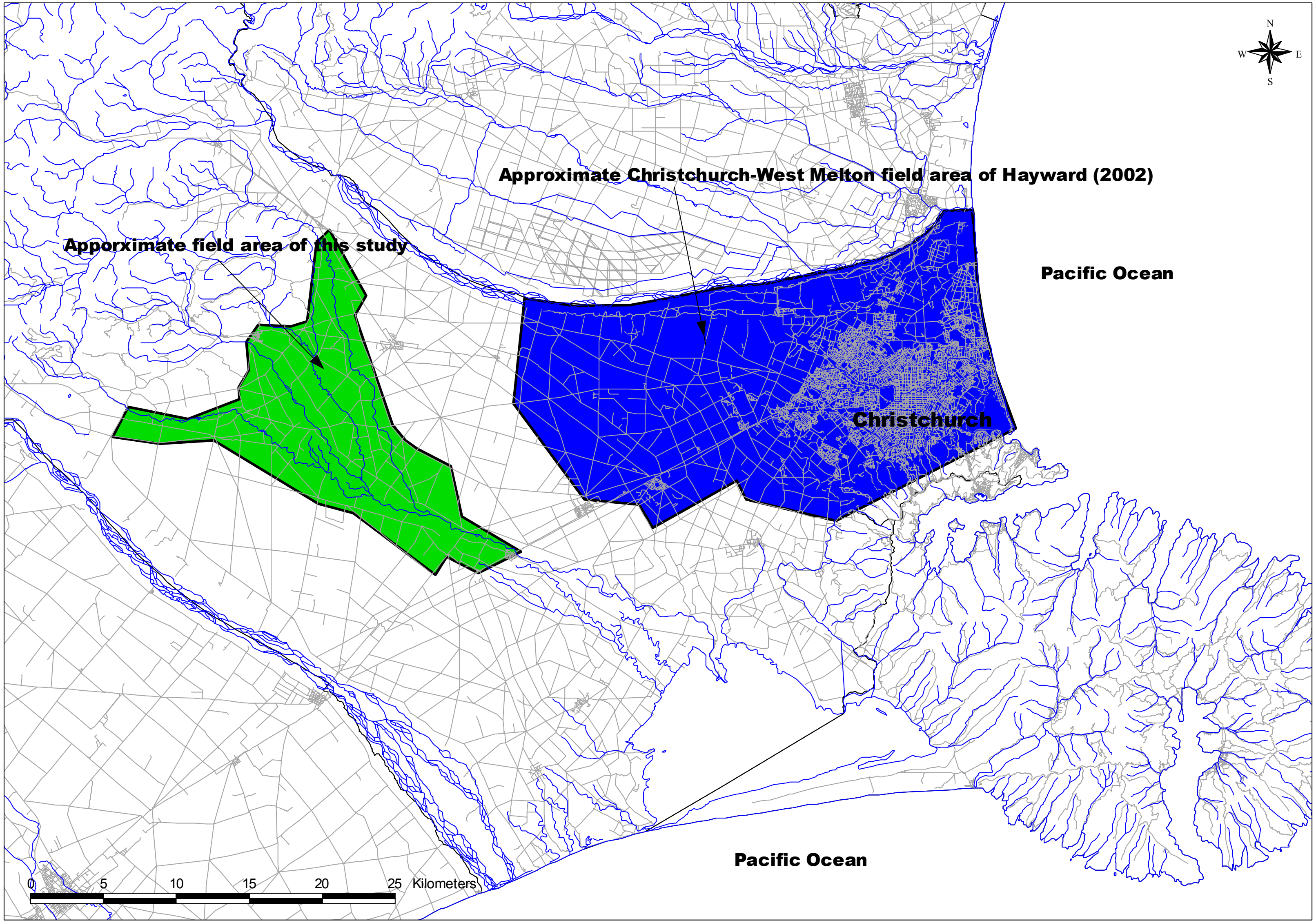
Appendix 5.2: δ^{18}O values of Canterbury rivers.

Weeks	Date	Waimakariri R	Selwyn R	Rakaia R
	1977/78			
0.2	02-Sep	-9.9	-9.0	-10.3
0.7	05-Sep	-10.1	-8.7	-10.3
1.1	08-Sep	-9.9	-8.7	-10.3
1.4	10-Sep	-9.9	-8.7	-10.2
1.9	13-Sep	-9.9	-9.1	-10.0
2.1	15-Sep	-9.8	-8.9	-10.0
2.4	18-Sep	-9.7	-9.1	-10.0
3	21-Sep	-9.6	-8.8	-9.7
3.4	25-Sep	-9.9	-8.6	-9.9
3.9	27-Sep	-9.7	-8.6	-10.1
4.1	29-Sep	-10.5	-8.7	-10.0
4.4	01-Oct	-10.4	-8.9	-10.3
4.7	03-Oct	-10.2	-8.9	-10.4
6	10-Oct	-9.7	-9.5	-10.5
7	17-Oct	-10.4	-9.2	-9.7
8	24-Oct	-9.8	-9.4	-9.9
9	30-Oct	-9.4	-9.5	-9.9
10	07-Nov	-9.4	-8.9	-9.2
11	14-Nov	-9.6	-9.0	-9.7
12	21-Nov	-9.5	-8.7	-9.6
13	28-Nov	-9.5	-9.1	-9.5
14	05-Dec	-9.4	-9.0	-9.5
15	12-Dec	-9.7	-9.1	-9.8
16	19-Dec	-9.3	-9.0	-9.5
17	26-Dec	-9.4	-9.4	-9.6
18	04-Jan	-9.2	-9.0	-9.5
19	11-Jan	-9.6	-9.1	-9.4
20	18-Jan	-9.1	-9.0	-9.5
21	24-Jan	-9.3	-9.1	-9.7
22	31-Jan	-9.4	-9.0	-9.6
23	06-Feb	-9.3	-9.0	-9.4
24	13-Feb	-9.2	-8.7	-9.3
25	20-Feb	-9.4	-9.0	-9.5
26	27-Feb	-9.2	-8.7	-9.3
27	06-Mar	-9.3	-8.9	-9.2
28	13-Mar	-9.4	-8.2	-9.5
29	20-Mar	-9.4	-8.7	-9.4
30	28-Mar	-7.7	-8.9	-7.6
31	04-Apr	-8.7	-9.1	-8.7
32	11-Apr	-9.0	-9.4	-9.2
33	18-Apr		-8.9	-9.2
34	25-Apr	-9.4	-8.9	-9.5
35	02-May	-9.5	-9.0	-9.6
36	09-May	-9.4	-9.0	-9.7
37	16-May	-9.9	-9.0	-10.1
38	23-May	-9.5	-9.0	
39	30-May	-9.7	-8.9	-9.8
40	07-Jun	-9.7	-9.0	-9.8
41	14-Jun	-9.7	-9.3	
42	25-Jun			
	Mean	**-9.55**	**-8.97**	**-9.67**
	se	**0.45**	**0.25**	**0.49**



Appendix 5.3

"Map showing location of Christchurch-West Melton study area of Hayward (2002)"


N
W
E
S
Approximate Christchurch-West Melton field area of Hayward (2002)
Apporximate field area of this study
Pacific Ocean
Christchurch
Pacific Ocean
0
5
10
15
20
25
Kilometers

Appendix 6.1

“Tritium, CFC and SF_6 concentrations and ages”

Sample ID	Calculated from Ar & N_2[1]		Calculated atmospheric partial pressure (pptv)[2]			Age based on piston flow model (yrs)[3]		
	Temp °C	Excess air	CFC-11	CFC-12	SF_6	CFC-11	CFC-12	SF_6
L36/1288	7.5	6.2	3.3 ± 0.3	19.1 ± 1.7		49	48	
L36/0317	11.9	2.3	151.7 ± 3.1	1005.7 ± 7.8		25	C	
L35/0205	9.1	4.8	48.5 ± 1.7	300.9 ± 7.9	3.81	35	24	8
L35/0171	9.6	9.9	167.3 ± 0.5	454.5 ± 0.9	4.62	24	16	4
L35/0596	12.3	0.0	217.0 ± 12.0	547.5 ± 21.7	5.50	18	4	0
L36/1635	10.1	4.5	2.2 ± 1.5	6.2 ± 3.2		51	55	
L35/0666	10.7	2.4	93.3 ± 0.9	372.6 ± 2.7	4.23	30	20	6
L36/0059	11.5	2.6	114.0 ± 0.8	428.4 ± 1.0		29	17	
L36/1334	10.8	3.0	20.7 ± 9.2	110.2 ± 35.6		41	35	
L36/1651	11.7	0.3	80.0 ± 0.5	296.7 ± 1.2	3.79	32	24	8
L36/1003	10.8	-0.3	469.3 ± 11.8	730.6 ± 12.5	5.35	C	C	1
L36/0994	12.2	2.9	216.5 ± 3.6	716.5 ± 7.4		18	C	
L36/0579	9.8	1.8	156.1 ± 2.0	515.6 ± 1.9		25	11	

[1] See Figure 2 (Stewart, 2005). Excess air is given in mL(STP)/kg.
[2] Pptv is parts per trillion by volume, and 1 pptv signifies a ratio of 1×10^{-12}.
[3] Piston flow ages are calculated assuming that all of the water in the sample has the same age (i.e. there is no mixing). 'C' means the sample is contaminated; i.e. it contains greater than ambient amounts of the gas (see Figure 1).

Sample ID	$\delta^{18}O$ (‰)	Tritium (TU)[1]	Mean age (in years) based on the EPM model shown: Tritium		CFC-11	CFC-12	SF_6	Recommended mean age (years)
		Scale = 1.25	20%	50%	50%	50%	50%	
L36/1288	-8.8	0.09 ± 0.02	61	90	78	71		90
L36/0317	-8.6	2.19 ± 0.05	1,30,46	1,~39	27	C		~39
L35/0205	-8.7				48	26	8	48
L35/0171	-8.7				25	15	3	25
L35/0596	-8.8				15	0-3	0	15
L36/1635	-8.6	-0.02 ± 0.02	>70	>95	82	85		>95
L35/0666	-8.9				37	21	6	37
L36/0059	-8.8	2.03 ± 0.04	1,29,46	1,~39	33	17		~39
L36/1334	-8.7	0.94 ± 0.04	51	70	59	46		70
L36/1651	-8.9				40	26	8	40
L36/1003	-8.7				C	C	1	?
L36/0994	-8.5				17	C		17
L36/0579	-8.8				26	9		26

[1] One unit of tritium (TU) corresponds to one ^3H atom per 10^{18} atoms of hydrogen.

Figure 2.9 Geological Map of the upper Selwyn Plains (modified from Wilson, 1989).